System Fault Diagnosis Using Fault Tree Analysis

By

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A Doctoral Thesis
Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

June 2008

Abstract

Fault tree analysis is a method that describes all possible causes of a specified system state in terms of the state of the components within the system. Fault trees are commonly developed to analyse the adequacy of systems, from a reliability or safety point of view during the stages of design. The aim of the research presented in this thesis was to develop a method for diagnosing faults in systems using a model-based fault tree analysis approach, taking into consideration the potential for use on aircraft systems.

Initial investigations have been conducted by developing four schemes that use coherent and non-coherent fault trees, the concepts of which are illustrated by applying the techniques to a simple system. These were used to consider aspects of system performance for each scheme at specified points in time. The results obtained were analysed and a critical appraisal of the findings carried out to determine the individual effectiveness of each scheme.

A number of issues were highlighted from the first part of research, including the need to consider dynamics of the system to improve the method. The most effective scheme from the initial investigations was extended to take into account system dynamics through the development of a pattern recognition technique. Transient effects, including time history of flows and rate of change of fluid level were considered.

The established method was then applied to a theoretical version of the BAE Systems fuel rig to investigate how the method could be utilised on a larger system. The fault detection was adapted to work with an increased number of fuel tanks and other components adding to the system complexity. The implications of expanding the method to larger systems such as a full aircraft fuel system were identified for the Nimrod MRA4.

Acknowledgements

Firstly I would like to thank my supervisors Prof John Andrews and Dr Lisa Bartlett for the opportunity of carrying out this research and their guidance, advice and support throughout its duration.

Thanks also to my industrial sponsors at BAE Systems including Clive Downes, Tony Martin, Angus Murray, John Pearson, Mike Walsh and Andrew Williams for their helpful advice and for looking after me during my work placements in their company. In addition special thanks go to the people from the Nimrod Fuel System who provided me valuable information on their aircraft.

I would also like to thank the people of the Aeronautical and Automotive Engineering Department and the students that I have sat with for helping to keep me motivated and enthusiastic.

A huge thank you must go to my family for their endless love, support and encouragement throughout this time, without which this work could not have been completed.

Final thanks go to my Fiancé, Graham, for his support, understanding and for always believing in me.

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Nomenclature

ACTIVE	-	Flow Phase Through Valve V2
$\overline{\text{ACTIVE}}$	-	NOT Flow Phase Through Valve V2
CBM	-	Condition Based Maintenance
C_i	-	Minimal cut set i
Ci $(1 \leq i \leq 2)$	-	Controller i
CiFH $(1 \leq i \leq 2)$	-	Controller C_i Fails High
$\overline{\text{C}i\text{FH}}$ $(1 \leq i \leq 2)$	-	Controller C_i Does NOT Fail High
CiFL $(1 \leq i \leq 2)$	-	Controller C_i Fails Low
$\overline{\text{C}i\text{FL}}$ $(1 \leq i \leq 2)$	-	Controller C_i Does NOT Fail Low
c_j	-	Associated test cost j
DFD	-	Design For Diagnosability
DFT	-	Design for Testability
DORMANT	-	No Flow Phase Through Valve V2
$\overline{\text{DORMANT}}$	-	NOT No Flow Phase Through Valve V2
EGI	-	Enhanced Global-positioning-system Inertial-navigation-unit
F	-	Flow
FTA	-	Fault Tree Analysis
FTVi $(1 \leq i \leq 3)$	-	Flow Through Valve Vi
FUG	-	Fuel Gauging and Levelling Sensing System
FUM	-	Fuel Management System
HF	-	High Flow
I_{C_i}	-	Fussell-Vesely measure of minimal cut set importance
J	-	The average cost
LF	-	Low Flow
NF	-	No Flow
NFTV1i $(1 \leq i \leq 3)$	-	No Flow Through Valve Vi

NWMS	-	No Water from Mains Supply
NWOST	-	No Water in the Overspill Tray
$\overline{\text{NWMS}}$	-	NOT No Water from Mains Supply
p	-	'*a priori*' probability being in system state s_i
$P(C_i)$	-	Probability of failure of minimal cut set i
Pi $(1 \leq i \leq 6)$	-	Pipe i
PiB $(1 \leq i \leq 6)$	-	Pipe Pi is Blocked
$\overline{\text{P}i\text{B}}$ $(1 \leq i \leq 6)$	-	Pipe Pi is NOT Blocked
PiF $(1 \leq i \leq 6)$	-	Pipe Pi is Fractured
$\overline{\text{P}i\text{F}}$ $(1 \leq i \leq 6)$	-	Pipe Pi is NOT Fractured
$p(s_i)$	-	The probability of the system being in state s_i
$P(T)$	-	Probability of top event
Q_{EXACT}	-	System unavailability
Q_{LB}	-	Lower bound
Q_{MCSU}	-	Minimal cut set upper bound
Q_{RE}	-	Rare event upper bound (Rare event approximation)
$Q_{SYS}(t)$	-	System unavailability
$q(t)$	-	Component unavailability (failure probability)
S	-	Finite set of system states
SDG	-	Signed Directed Graph
SHM	-	System Health Monitoring
s_i	-	System state i
Si $(1 \leq i \leq 2)$	-	Sensor i
SiFH $(1 \leq i \leq 2)$	-	Sensor Si Fails High
$\overline{\text{S}i\text{FH}}$ $(1 \leq i \leq 2)$	-	Sensor Si Does NOT Fail High
SiFL $(1 \leq i \leq 2)$	-	Sensor Si Fails Low
$\overline{\text{S}i\text{FL}}$ $(1 \leq i \leq 2)$	-	Sensor Si Does NOT Fail Low
t	-	Time
T	-	Finite set of available binary tests
t_j	-	Binary test j
TL	-	Water Tank Leaks
$\overline{\text{TL}}$	-	Water Tank Does NOT Leak
TR	-	Water Tank Ruptured
$\overline{\text{TR}}$	-	Water Tank is NOT Ruptured

TRAY	-	Overspill Tray
USMS	-	Utilities Systems Management System
VFi $(1 \leq i \leq 3)$	-	Volume Flow Rate Sensor i
Vi $(1 \leq i \leq 3)$	-	Valve i
ViFC $(1 \leq i \leq 3)$	-	Valve Vi Fails Closed
$\overline{\text{V}i\text{FC}}$ $(1 \leq i \leq 3)$	-	Valve Vi Does NOT Fail Closed
ViFO $(1 \leq i \leq 3)$	-	Valve Vi Fails Open
$\overline{\text{V}i\text{FO}}$ $(1 \leq i \leq 3)$	-	Valve Vi Does NOT Fail Open
WK	-	Working
WOST	-	Water in the Overspill Tray
$\lambda(t)$	-	Conditional failure rate
$\nu(t)$	-	Conditional repair rate

Chapter 1

Introduction

1.1 Fault Detection System Background

Advances in technology have brought about increased system complexity, therefore making fault detection, diagnosis and rectification a more difficult task to perform. Any type of system, however well it is maintained, will at some point encounter component failures during the course of its life cycle. This can cause a change in system function, a reduction in system performance or worse still result in downtime from operation. A number of components could fail simultaneously changing the symptoms exhibited by the faults individually, which may further increase the time taken to obtain a successful diagnosis. Some faults may never be discovered until certain parts of the system are used.

In the event of a failure, to lessen the impact on a system it is important that it is detected and the cause is diagnosed as soon as possible. Once a diagnosis has been made the problem can be rectified either by repairing or replacing the component, therefore returning the system to normal operation. Fast detection, diagnosis, and rectification in aircraft systems reduces the time taken for planes to be returned to service. In the case of autonomous robotic vehicles, detection and diagnosis of faults can aid the completion of successful missions. In chemical process plants the need to detect and diagnose causes of a safety critical failure in a system can be vital and an answer may be required within minutes, as a failure could result in an explosion, threatening the lives of workers and people living in the surrounding area.

A fault can be defined as [1]:

A fault is the identification of a non-permitted deviation of a characteristic property which leads to the inability to fulfill the intended purpose.

Some faults may occur slowly over time due to wear on the components, or they may become apparent when the particular area of the system it is located in gets used. Other failures could cause significant changes in system operation, for example a blockage in a pipe. There may also be failures that occur intermittently within the system depending on certain conditions or patterns, which leads to a recurring failure. Any failure may cause serious damage if no action is taken, whether this be rectification or reconfiguration of the system so that that part is shut down. Once a deviation from normal operation is found a diagnosis can be performed to ascertain the cause of failure. This is the fault detection process.

The process of diagnosing faults in a system has in the past been conducted by building up a knowledge base of faults through documenting failures and the methods carried out to repair them. The information was then available for use in the diagnosis of future failures. This is known as case-based reasoning. Today, a growing number of diagnostic systems are computer-based so history is documented in a computer database, making them quicker, easier and more efficient to use.

Price [2] considers a number of important factors when measuring the effectiveness of a diagnostic system. These include efficient construction, reasonable maintainability, adequate coverage, accuracy, minimum effort from the user, appropriate response time and good cost/benefit ratio. The importance of each of these factors will be dependent upon the system that is being diagnosed.

Efficient Construction

A diagnostic system needs to be efficient, used at the lowest possible cost and in the shortest possible time frame in order to be effective in obtaining a diagnosis. The importance of these factors will depend on the type of system being diagnosed and requirements specified.

Reasonable Maintainability

Any diagnostic system has to be maintained in order to ensure it provides an efficient level of fault detection. The equipment being diagnosed may also change over time, therefore ideally a diagnostic system should be easy to update with any changes that could potentially affect diagnosis.

Adequate Coverage

A diagnostic system should be able to detect a large proportion of the failures that can occur. However, the coverage of all faults may be a difficult process. For instance, a fault may occur in a part of a system that seldom gets used and would therefore remain undetected until required. The cost of development may also limit a full detection process.

Accuracy

Ideally a fault diagnostic system should be able to diagnose any possible failure correctly. In reality there may be numerous candidates for the cause of failure and in some cases the correct cause may not be present.

Minimum Effort from the User

A diagnostic system should only request information relevant to obtaining a correct diagnosis. A complex diagnostic system could require training to use adding to the cost and time investment, resulting in only a select number of workers knowing how to use it.

Appropriate Response Time

The time taken for a diagnostic system to perform a diagnosis will be dependent upon the system for which the diagnosis is being performed. Some systems such as chemical processing plants require a diagnosis within seconds of a fault becoming detected. For other systems the detection time is not as critical, but the faster a diagnosis is obtained the earlier work can begin to fix the problem and return the system to normal operation.

Good Cost/Benefit Ratio for Diagnosis

A cost/benefit ratio can be used to determine whether building a diagnostic system would be financially beneficial to a company. Costs incurred would be for running the tool, maintaining it and for its distribution. An efficient system would reduce the time taken to obtain a diagnosis, therefore increasing system availability and reducing downtime from normal operation. Some tools can continuously monitor a system for failures. These can detect failures as and when they occur, therefore enabling a faster diagnosis. The increased cost of monitoring continuously would have to be compared with the benefit of knowing the cause of failure quicker.

In the majority of cases fault detection systems are built after the development of the system they are designed for. In order to provide a more effective diagnostic strategy the design of a new system could take into consideration both 'design for diagnosability' (DFD) and 'design for testability' (DFT). Diagnosability is a measure of the ease of isolating faults in a system [3, 4]. DFD investigates each decision made throughout the process of the design stage of a system to see the effect it has on the system's diagnosability. DFT is a similar measure to DFD but focuses on how accessible a system is to test and maintain, which leads to the diagnosability of the system. DFT is also applied at each stage of the design phase, considering how maintainable a device is and if, or how, the testability can be improved. The drawback of both DFD and DFT are that they produce extra work during the design phase and may lengthen the time taken and increase the manufacturing costs [2]. These disadvantages can be justified by greater savings made later on during the system life cycle.

A way of determining how effectively a system is performing is to use a set of sensors to determine the system health, performance and safety. The is known as 'system health monitoring' (SHM). SHM can be used to answer questions such as [5]; 'is the system functioning correctly?', 'what is wrong with the system?', 'is the state of the system as expected?', 'what needs to be fixed to ensure the system functions correctly?'. Notable capabilities that fall under SHM include fault detection and identification, failure prediction, modelling or tracking degradation, maintenance scheduling and error correction [6]. Condition based maintenance (CBM) is an example of SHM that identifies the requirements of a system based on its current operating conditions. It uses information gathered from a system to detect, analyse and correct equipment before a failure is displayed [6, 7].

1.2 Types of Fault Detection System

1.2.1 Rule-Based Diagnostic Systems

A rule-based diagnostic approach traces the causes of a fault using a knowledge base devised by experts in the system domain for which the diagnosis is being performed. This knowledge is represented in the form of 'IF-THEN' rules, the 'IF' part being the condition and the

'THEN' part the consequence or action taken as a result of the condition being true. Each rule provides an independent piece of knowledge about the system behaviour that can assist in solving the overall problem. There can be multiple conditions specified using logical operators. Consider the following rules as discussed in [8]:

IF A THEN B
IF B THEN C
IF C THEN D

If A is true then it can be deduced or 'logically inferred' that D is also true using these three rules. They can be illustrated as shown in Figure 1.1.

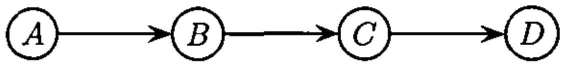


Figure 1.1: Illustration of IF-THEN rules

Each rule relates to a question or test for which the outcome is in a yes/no format. The answer determines which test to carry out next. This type of diagnostic system is simple to use and each rule gives the user more of an idea of what the problem is and how to solve it. Rules may also be implemented in any order. These qualities make rule-based expert systems one of the most successful products to emerge from artificial intelligence [8]. There are however a number of limitations. A system with a large set of rules may be slow in obtaining a diagnosis as there would be more testing to carry out. The rule-based system cannot learn from experience unlike an expert human, and also will not be able to automatically modify its knowledge base. It is often difficult to obtain a full correct set of rules for a system, either because the expert has no time to update the tool or due to the complexity of the system being diagnosed.

1.2.2 Case-Based Diagnostic Systems

Case-based reasoning is a methodology that solves a new current problem in a system using the solutions from similar past problems and experience rather than theory. Solutions can therefore be obtained quicker than having to solve a problem from the beginning. Each solution obtained can be used over and over again to solve other problems in the system. Once a failure has been identified there are four main stages of analysis; retrieve, reuse, revise and retain, as shown by Aamodt [9].

Retrieve

Obtain the case that is most similar to the new problem from the case-based memory of past solutions. The information gathered should include a problem description and details of exactly how the problem was solved.

Reuse

The solution of the case selected is adapted to meet the requirements for solving the new problem. Modifications made can be major or minor.

Revise

A solution to the new problem is obtained and an evaluation indicates how effective this is. If necessary, additional modifications to the solution can then be made.

Retain

Once a solution has been found it can be stored with the other past solutions as a case in the case-based memory. The information should include a description of the problem and details of how it was solved. This can then be used to help solve new problems in the future.

Case-based reasoning is not as effective when making a diagnosis of large complex systems where there could be a large number of possible past solutions to choose from to obtain a new solution. Also, relatively new systems may not have a comprehensive case-based memory to solve the problems. More details about case-based reasoning can be found in Price [2], Kolodner [10] and Watson [8].

1.2.3 Model-Based Diagnostic Systems

Model-based reasoning is a deductive approach in which faults are identified by comparing behaviour that is actually being observed from a system against an expected model. This model is generated depending on the operating conditions and compared to what is actually being observed in the system. Any differences between the observed and predicted behaviour indicates that a failure has occurred. Diagnosis can then be performed to locate and determine the potential causes of this failure and obtain the most likely cause. The user would also need to decide which part of the system to model, whether it be the physical components or the processes of the system, and how to get a diagnosis from the observed information obtained.

1.2.4 Real-Time Diagnostic Systems

A system is monitored continuously in order to detect faults as and when they occur in real-time. The diagnostic system is therefore automated to run alongside the system for which diagnosis is being performed. Once a deviation from normal system behaviour has been detected a diagnosis is performed to obtain the most likely causes of failure. Techniques used for diagnosis include case-based and model-based reasoning. Depending on the system it may be possible for the diagnostic tools to also repair certain faults automatically. The system could have built-in redundancy so that it is able to keep functioning whilst system repairs are carried out. For other real-time tools it may be enough to indicate that a fault has occurred in the system and leave it to the operator to deal with.

Features that real-time systems can have include [2]: continuous monitoring and problem identification, changes in monitoring conditions, hard real-time constraints, reasoning about uncertainty and time and autonomous decision making.

Continuous Monitoring and Problem Identification

A feature of many continuously monitoring fault diagnostic tools is they can detect problems in a system while they develop rather than waiting for the failure to occur. Components can then be replaced as and when required prior to failure. Without monitoring, preventative maintenance is usually carried out and involves replacing components after so many hours of operation in order to reduce the likelihood of that part failing. This method can be very costly as components may be replaced with some life remaining and result in an increase in the overall maintenance.

Changes in Monitoring Conditions

In order to provide effective condition monitoring a diagnostic system must be able to differentiate between component states, which can be carried out using trends in system data. A component that is about to fail will differ in the way it functions compared to one that is working as there would be a slight variation due to wear. In the latter case alterations in the system operation could be made to adapt to these changes.

Hard Real-Time Constraints

The required response time when a fault is detected in a system may vary depending on the type of system being diagnosed. In some cases the system may be able to carry on functioning with the failure present, although not as efficiently. The diagnosis time can depend upon the time it takes for the system to react to the failure and also the type of failure that has occurred.

Reasoning About Uncertainty and Time

System data can be analysed over time in order to develop a set of trends. A possible problem may be identified, but this could take time to develop before it is certain that an actual failure exists. A trend could be used to indicate the most likely outcomes to enable a fault to be identified as soon as possible.

Autonomous Decision Making

The diagnostic tool must be able to decide on the cause of action required for a detected failure as quickly as possible so to minimise its effect. This decision is made automatically without any operator intervention. Therefore, there must be confidence in the diagnostic system to identify failures.

1.3 Diagnostic System Features

There are a number of features that a diagnostic system should have, including: problem identification/fault detection, fault localisation, fault identification and fault diagnosis capabilities. The significance of each of these may vary depending upon the system use. Once a fault has been diagnosed a decision as to whether to repair/replace the component or allow the system to continue running in an alternative operation through system redundancy can be made.

Other desirable diagnostic characteristics include the ability of the system to provide quick detection and diagnosis, the isolability of failures, system robustness and the adaptability of a system to a change in conditions as defined by Venkatasubramanian [11].

Problem Identification/Fault Detection

The first step before trying to obtain a diagnosis is to identify that a problem has occurred. A problem may be identified using readings from sensors. The time at which the failure first occurred may also be recorded. The readings can be compared with those expected and thus identify any deviations encountered. Another way of identifying a problem could be by human observation.

Fault Localisation

Once a problem has been recognised as being present in the system the potential area in which the deviation has occurred is located in order to restrict the possible causes of failure.

Fault Identification

Once the potential fault area is located, the next phase is to identify the possible causes of failure. This may carried out using a fault detection method.

Fault Diagnosis

The next step is to identify the component or components in the system that have caused the actual failure to occur from the list of possibilities. In the majority of cases a system failure will be the result of one faulty component. However, the possibility of multiple failures cannot be dismissed, especially within more complex systems.

Once a diagnosis is made the decision to repair/replace the faulty components or allow the system to run in an updated mode of operation has to be made. This will be dependent upon whether the fault or faults are tolerable or intolerable within the system. If tolerable then the system can carry on with the failure present through use of redundancy. This type of failure may also be repaired whilst the system is in operation. If intolerable the system would have to be shut down and the problem rectified before returning to a working status. A flow diagram of the process of diagnostic system features is shown in Figure 1.2.

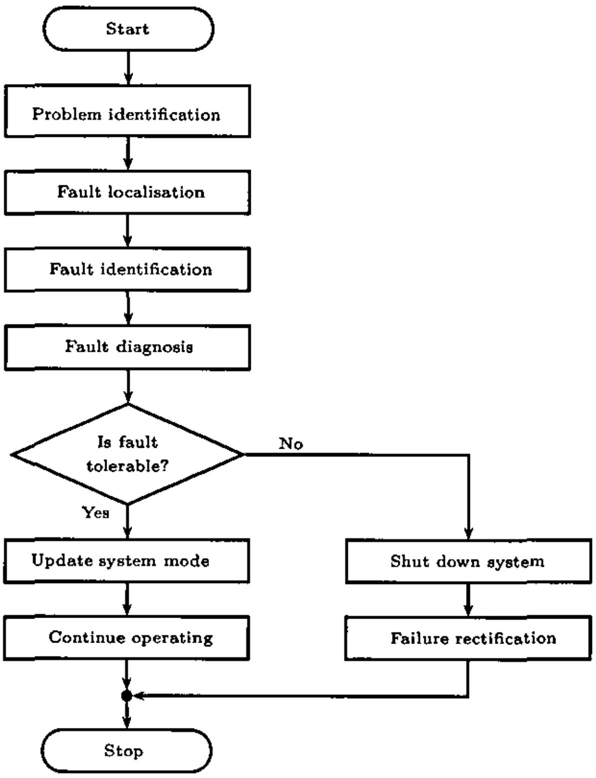


Figure 1.2: Diagnostic process flow chart

1.4 Deficiencies in Diagnostic Systems

The following are possible deficiencies that could occur in diagnostic systems:

- The time taken to perform a diagnosis - a diagnostic system that takes a long time to perform a diagnosis is not very efficient.
- Some diagnostic methods are not equipped to deal with the increasing complexity of systems.
- The accuracy of the diagnosis obtained - diagnostic tools may not always produce accurate results.
  - Some diagnostic tools only generate a list of possible failures to a certain likelihood of occurrence.
  - Some diagnostic tools only diagnose single failures in systems, when there may be multiple failures that have occurred in order to cause system failure.

- Some diagnostic tools do not take into consideration the components that are known not to have failed - working component states. These could be used to eliminate possible causes of failure.
- There may be erroneous causes of the symptoms listed.
- There may be incomplete causes of the symptoms listed.

1.5 Research Project Objectives

Fault trees are commonly developed and analysed to check the adequacy of systems, from a reliability or safety point of view, at the design stage. Since they express the causes of system failure the aim of the research is to develop a method for diagnosing faults in systems using a model-based fault tree analysis (FTA) approach. This will initially consider aspects of system performance observed at specified points in time and then be extended to consider dynamics. The following objectives have been listed in order to achieve this aim:

- Review the existing fault diagnostic techniques applied to systems.
- Develop a fault diagnostic method for steady-state conditions and demonstrate its capability on a simple water tank level control system in order to predict single and multiple failures that cause a system fault.
- Develop a fault detection demonstrator that, given a set of sensor readings, can compare these with the model behaviour for the system and generate a set of potential causes of failure for the system.
- Incorporate dynamics into the analysis to take into consideration system transient effects.
- Once a method is established apply it to a larger system example - the BAE Systems fuel rig physical model will be utilised for this purpose. Refine the fault detection process as needed to cope with the increased system complexity.
- Identify the implications of expanding the method to larger systems such as a full aircraft fuel system.

Chapter 2

Literature Review

2.1 Introduction

There are a number of types of fault detection system, including rule-based, case-based, model-based and those using real-time analysis, as introduced in Section 1.2. It would be difficult to develop a diagnostic method using case-based reasoning that could be used on any type of system as this strategy depends on previous history of failures to diagnose faults. As one of the objectives is to develop a diagnostic method for use on large and complex systems case-based reasoning will not be investigated further. Rule-based and model-based diagnostic systems are discussed in more detail in this chapter, including real-time qualities. A number of the techniques contain aspects of more than one type of fault detection system, therefore these have been placed into the most appropriate category.

2.2 Rule-Based Diagnostic Systems

2.2.1 Introduction to Rule-Based Systems

Rule-based reasoning uses a knowledge base developed by experts in that area in order to diagnose any faults the system may encounter. The rules for the system are used to direct this knowledge to ascertain a cause of failure. A number of diagnostic systems investigated have been built using a rule-based strategy. These are now described in order to illustrate how this system type has been utilised. A variety of analysis techniques have been used including sequential testing, signed directed graphs (SDGs), FTA and Bayesian networks.

2.2.2 Sequential Testing

Sequential testing is a method that can be used to perform system diagnosis by generating a sequence of tests that lead to a series of potential causes. Each test carried out incurs an associated cost. The aim is to obtain a diagnosis at the lowest cost possible, and therefore acquire an optimal solution to the problem. Solutions have been derived using numerous optimisation algorithm techniques [12–21].

The test sequencing problem [17,21] can be described as the four-tuple (S, p, T, c) where S is a finite set of system states, p is an '*a priori*' probability of the system being in state s_i before diagnosis takes place, T is the finite set of available binary tests, t_j, and c_j are the associated test costs.

Each test carried out divides the list of potential faults into two subsets: tests that pass, and those that fail. The tests and states can be interpreted using decision trees, with branches representing the test outcome (pass/fail), states are represented by the square terminal nodes and circular nodes are the tests carried out, as shown in Figure 2.1. Left-hand branches in decision trees illustrate the tests that have passed ('P') and right-hand branches are those which have failed ('F').

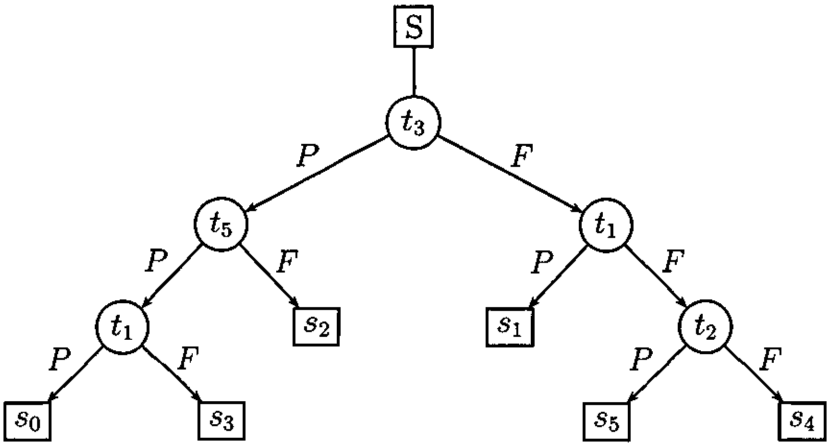


Figure 2.1: An example decision tree

There are a number of different types of test that can be carried out, the main ones being symmetrical and asymmetrical testing. Symmetrical tests can either be definitely passed or failed, and so $A \cap B = \emptyset$, (where A represents the tests passed and B those failed). At least one state will occur in both subsets A and B in asymmetrical testing. Therefore the system state could have failed a test but still be listed as a potential cause of the next test that takes place, and so in this case, $A \cap B \neq \emptyset$. Asymmetrical testing leads to multi-valued testing, in which case the tests have an arbitrary number of possible outcomes [21].

Pattipati and Dontamsetty [22] have presented a sequential approach that identifies a faulty module in a system rather than the individual faults themselves. The testing algorithm branches to a subset of states belonging to the same module and then ceases when it has found the module in which rectification is required. The modular approach also offers the option of replacing a whole module within a system rather than the exact failure. This is only cost-effective if the cost of replacing a faulty module is less than applying more tests to obtain the exact cause of failure.

The sequential diagnostic tool [21] carries out a series of tests to determine the system status at a certain point in time using information about which symptoms are exhibited when faults are present. This determines the best sequence to conduct the tests in order to locate the fault condition in the cheapest (or quickest) way.

Consider a car braking system [21] with 7 possible system failure states and a fault-free state as shown in Table 2.1. These are represented by $S = \{s_0, s_1, \ldots, s_7\}$, with s_0 being the fault-free state. System status can be indicated by testing 9 failure symptoms, $T = \{t_1, t_2, \ldots, t_9\}$.

		t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
	Failures / **Failure Symptoms**	**Fading brake pedal**	**Low brake pedal**	**Pedal pulsates**	**Brake drag**	**Abrupt response**	**Weakened brake force**	**Pulling the vehicle to one side**	**Non-uniform braking**	**Strange noises (squeals and grinding)**
s_1	Lack of brake fluid	•	•							
s_2	Air in the brake lines	•		•						
s_3	Worn pads				•					
s_4	Wet or oily pads				•	•		•	•	
s_5	Error in the control mechanism				•		•	•		
s_6	Damaged wheel bearings			•		•		•	•	•
s_7	Damaged wheel cylinder	•	•		•		•	•	•	

Table 2.1: Car braking system

Table 2.1 indicates where a test is used in a path leading to the identification of the system state. For instance, the failure 'lack of brake fluid' would be identified through the failure symptoms 'fading brake pedal' and 'low brake pedal', represented by '•'. Each test t_j that leads to a system state incurs a cost, c_j, which in this particular example are all assumed equal to 1. The information from Table 2.1 can therefore be written in matrix form, as shown in Table 2.2, where '1' in the matrix corresponds to '•'. Fault probability '$p(s_i)$'

in the right-hand column of the matrix is the probability of the system being in state 's_i' before diagnosis takes place.

System State	Tests									Fault Probabilities
s_i	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	$p(s_i)$
s_0	0	0	0	0	0	0	0	0	0	0.95
s_1	1	1	0	0	0	0	0	0	0	0.005
s_2	1	0	1	0	0	0	0	0	0	0.01
s_3	0	0	0	1	0	0	0	0	1	0.02
s_4	0	0	0	1	1	0	0	1	0	0.00375
s_5	0	0	0	1	0	1	1	0	0	0.00375
s_6	0	0	1	0	1	0	1	1	1	0.00375
s_7	1	1	0	1	0	1	1	1	0	0.00375
Costs c_j	1	1	1	1	1	1	1	1	1	

Table 2.2: Braking system matrix

The order in which tests are carried out in a procedure can be illustrated using a diagnostic decision tree, as shown in Figure 2.2. The average cost J of a procedure can be obtained from the equation:

$$J = \sum_{i=0}^{m} \sum_{j=1}^{n} \alpha_{ij} p(s_i) c_j, \tag{2.1}$$

where α_{ij} is 1 if test t_j is used in the path leading to the identification of system state s_i, and zero otherwise (represented in a binary format). The aim is to minimise J, i.e: to obtain the lowest possible or optimal cost.

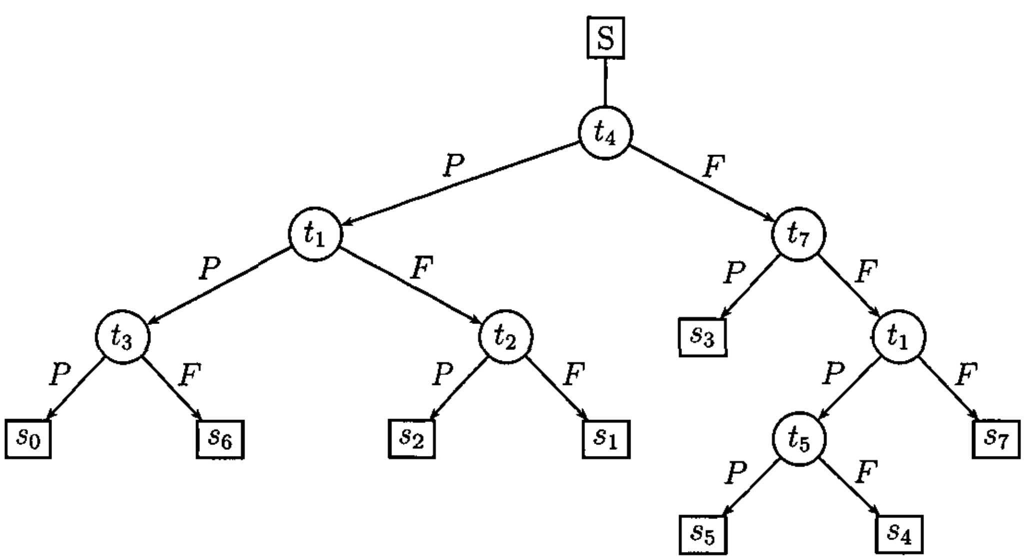


Figure 2.2: Optimal sequential diagnostic decision tree for the brake system with symmetrical tests

There can be more than one solution obtained to the problem. These may vary in cost depending on the ordering of the tests. The optimal solution to the problem is one that yields the lowest cost, of which there may also be more than one possibility. Substituting the values for Figure 2.2, which illustrates an optimal solution, into Equation 2.1 and gives $J = 2.9875$.

The methods described by Pattipati [17], Pattipati and Dontamsetty [22], Žužek *et al.* [18, 19, 21] and Biasizzo *et al.* [20] are limited to situations where only a single fault is expected to exist at any point in time; they do not take into consideration multiple component failures. Instead it is assumed that the system tests would be applied frequently enough to ensure that only one component failure has occurred. There is still the chance however that two failures could occur within the time frame that the system is checked, which makes diagnosis difficult. In the situation where two failures reveal only the symptoms of one failure this masks the faults, leading to incorrect diagnosis. Once the visible failure is rectified the tool would have to be used again to try and ascertain if any other failures are present.

The sequential testing approach has been extended to deal with the occurrence of multiple failures in systems using the single fault strategy as a building block for the expansion. The first step made by Shakeri *et al.* [23] considered extending the single fault strategy by isolating fault candidates in the sequential diagnostic tree, resulting in the identification of single or multiple failure possibilities. The idea of the multiple failure strategy is that a faulty component is replaced when identified. The system is checked again to see if the problem has been rectified by testing the system with the test that failed and all remaining tests not yet carried out. This continuous testing will identify whether the correct fault has been obtained or if a failure has been masked. It also identifies if there are any other failures with the system. There is however a high probability that some of the components replaced may not be faulty resulting in higher costs. The system could also encounter reduced system functionality for longer periods of time or even downtime from operation because of time taken to diagnose and rectify the problem. Also, this method is still only checking for single failures, just the process of testing for failures is carried out again once a failure has been rectified.

The investigations of continual testing for single failures to obtain multiple possibilities led to the development of a set of strategies that can isolate multiple definitely failed components at the same time. Each test can automatically indicate a failure of some kind in the system and more than one failure state for each test can be obtained in order to allow for the occurrence of multiple faults. Each test has an associated action that is carried out, therefore if a test fails then a failure state can be identified before the bottom of the decision tree is reached. This allows numerous failures to be identified. One of the main problems with this method is the large computational complexity that is encountered when dealing with multiple failures in a system and it has been suggested that to overcome this problem the test strategy should be generated 'on-line' as stated in Shakeri *et al.* [23]. Tests carried out in the analysis have been assumed to be perfectly reliable but in reality this may not be the case. Unreliable test sequencing problems have been considered in previous work carried out by Raghavan *et al.* [24], but only for single component failures. Finally, the failure signature (indicates all tests t_j that monitor a state s_i) of a multiple fault was assumed to be the union of failure signatures for individual faults, but this is not always the case [23] (i.e. failure states are independent).

A diagnostic system can be built to represent and automatically traverse diagnostic fault trees [2], which have the same structure as a sequential diagnostic tree, as shown in Figure 2.3. A diagnostic fault tree can be constructed in either an expert system shell or in a conventional programming language. This makes it easier to handle large complex trees that may spread over numerous pages if drawn out by hand, thus reducing the possibility of operator error. Automation enables the diagnostic system to follow the traversal progression and store detailed information with regards to each test and repair procedures to be carried out once a diagnosis has been ascertained.

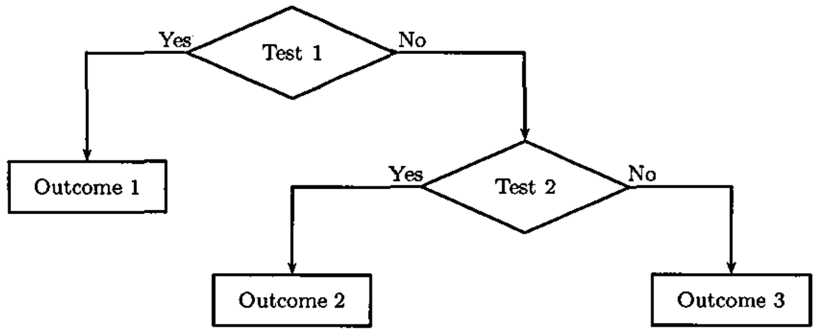


Figure 2.3: Simple diagnostic fault tree

An automated diagnostic system containing a diagnostic fault tree can be easily implemented and any alterations to the tree can be carried out in a straight forward manner, making the strategy reasonable to maintain. Automation also makes the more complex branches in the tree easier to illustrate, for instance the user may wish to have more than two possible outcomes from the questions asked. Should a tree become too large it can be split into appropriate tree sections in order to make it more user friendly.

The implementation phase of diagnostic fault trees can be a lengthy process and brings with it the risk of introducing possible errors into the trees. These problems can be omitted from the analysis by using a tool that automatically develops the diagnostic trees, giving the user a graphical output. The tool then creates a computer program from the diagnostic fault tree information and lessens the possibility of the user introducing programming errors into the system. Three examples of tools that generate a diagnostic system from diagnostic fault trees are GRAF2, TestBench^{TM} and GRADE^{TM}.

There are a number of disadvantages to using diagnostic fault trees. A tree may have to be updated on a regular basis in order to meet the demands and changes made in a system, for instance if a new component is added to a system then this could incur a failure that would need to be registered in the trees. Diagnostic fault trees could also get very large, making them more difficult to handle and maintain. There may be a difficulty in drawing a diagnostic fault tree for a new system that has no listed fault diagnostic history. The diagnostic fault tree approach is best employed in situations where a failure has caused a system to stop working and needs to be repaired in order to get back to its normal operating mode. The technique would not be as suitable for continuously monitored systems or ones that reconfigure their operation with the presence of a failure as the trees cannot account for this.

2.2.3 Signed Directed Graphs

Signed directed graphs (SDGs) can be used to illustrate the propagation of failures through a system and are most noted for their use in the chemical processing industry. A SDG consists of a set of vertices or nodes and edges. Each node represents a system process variable or the failure of a component. In the event where one variable has an affect on another an edge can be drawn to define a relationship between the two nodes. Edges are always directed from the independent variable to the dependent one, as indicated by the direction of the arrow. When there are a number of edges connecting the same two nodes, only one edge can be true at any time as they are mutually exclusive.

SDGs use signs (+) or (-) on the arcs to indicate whether the cause or effect change in the same or opposite directions respectively. Each node in the graph is also assigned one of three values, these being normal, higher or lower and (0), (+) or (-) are used to represent these respective results. SDGs can also contain conditional arcs that only become active if this condition is met. An example of a simple SDG is shown in Figure 2.4.

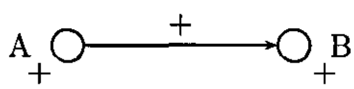


Figure 2.4: A simple signed directed graph

A method was devised by Kramer and Palowitch, Jr. [25] to identify the possible causes of process disturbances by creating SDGs in order to show interactions within a system. SDGs are used to develop a fault model, resulting in a set of directed trees that branch out from a given root node. Each node is representative of the origin of a fault and the branches indicate the propagation of the failure. Once the fault origin is located, in order to reduce the analysis, any nodes that do not represent a sensor - unless they are a potential root node - are removed and replaced by a single edge in order to leave the branches of interest for the diagnosis.

The reduced SDG is converted into a set of logical statements or 'rules' to ascertain the failure. For a branch $A \xrightarrow{+} B$ 'if A is 1 then B will be 1 or 0', 'if A is 0 then B must be 0' and finally 'if A is -1 then B is -1 or 0'. Similar results can be obtained for $A \xrightarrow{0} B$ and $A \xrightarrow{-} B$. Logical functions can be defined for each type of branch and these are evaluated to obtain a diagnosis. Kramer and Palowitch, Jr. concluded that only single failures could be identified using this technique and numerous possibilities were ascertained, some of which were incorrect. In other cases the true failure was not included in the list of possibilities, which often was encountered in control loops due to the presence of non-single transitions (changes of sign). Correct diagnosis is only guaranteed in the case where all variables use a single transition [25].

The method was extended by Chang and Yu [26] to try and overcome the problems that were identified by Kramer and Palowitch, Jr. The SDGs are simplified additionally considering results from steady-state analysis to improve the diagnostic solution. System state information is used to create arcs between certain nodes in order to depict the movement of a system from one state to another, therefore creating modularity. Additional process knowledge is sometimes required to indicate the effect most dominant in the fault transmission. The problem of obtaining a diagnosis for non-single transients is considered for the case of control loops by developing a set of rules for use during a transition.

Tarifa and Scenna [27,28] present a rule-based method for diagnosing faults in systems using SDGs, adapted from the technique used in Kramer and Palowitch, Jr. [25]. Qualitative modelling of a system is conducted using SDGs and from this a set of rules - for each of the sectors it is divided into - are created off-line. The on-line stage is executed by the system detecting an abnormality in sensor outputs. Fuzzy logic (takes into consideration partial truth as well as values that are completely true or completely false as in Boolean logic) is used to evaluate the set of rules obtained from the SDG. This type of logic was found to be better for evaluating the rules as less information was lost. The method was used on a larger system in [28] by building the SDG in sectors to deal with the size. There is still a heavy computational cost involved, especially in large examples with more rules to evaluate.

2.2.4 FTA

FTA is a deductive technique used in the safety and reliability assessment of systems to identify the causes of a specified system failure mode using a 'what can cause this' approach. The idea was first developed in the early 1960s by H. Watson [29] at Bell Telephone Laboratories and has become one of the most widely used reliability modelling techniques. Fault trees have also been noted for use in the development of diagnostic systems.

A fault tree can provide a symbolic representation of a failure mode that has been identified in a given system. This specified failure mode is called the 'top event', located at the top of the tree. The branches from this event lead to the possible causes of this failure (intermediate events) until component failure (basic) events are reached, terminating the logical development. More than one failure mode may be encountered in a system, therefore a fault tree should be drawn for each.

Madden and Nolan [30] and Nolan *et al.* [31] have investigated the notion of diagnosing failures within a system through inductively learning from previous examples. The approach uses a 'black-box model' of the system containing a knowledge base of what faults arise in components for given conditions, therefore no detailed description or analysis of the system to which it is applied is needed. An algorithm has been developed comprising of two main components, these being a fault tree induction module and a fault diagnosis module. The fault tree induction module uses example case data for both undesired events and for normal system behaviour that has been obtained using training data in the form of sensor recordings in order to generate fault trees. The algorithm builds a set of fault trees from this data for each identified system state. The trees are then translated into rules for use in the fault diagnosis module. This module takes a sensor recording that is supplied from the system and returns a set of possible states that the system could be in to the operator.

The diagnostic method uses aspects of both case-based and rule-based reasoning techniques and has been tested on an example system containing a variety of potential failures. The results obtained were compared with those based on an approach using neural networks [31] and the fault tree technique was found to be more effective. The method was extended to take into consideration multiple failures [32] by modifying the training data. Multiple failures are assumed to occur when either a failure that has already happened is not repaired and another materialises or if a known failure is in the system and another occurs intermittently. The technique learns overall from previous system experience, therefore it cannot be guaranteed to successfully diagnose all conditions obtained in the system in the future. The fault trees contain AND and OR logic, therefore there is no consistency check present within the trees.

Performing diagnosis using FTA will result in either one or a number of potential causes of failure. These potential causes are the minimal cut sets for the system. A method for diagnosis using a fault tree based approach to obtain minimal cut sets and repair information is described by Takahashi *et al.* [33]. Diagnosis takes place after a system has failed. A list of minimal cut sets or potential causes of failure are originally identified using FTA, which is used to indicate any deviations in the system behaviour from normal operation.

The actual cause of failure is identified by inspecting each component within the minimal cut sets. This part of the analysis is rule-based in structure as each component is checked to see if it is functioning or if it has failed. The method assumes there is a possibility the system failure can be caused by more than one minimal cut set as not all the failures may be identified within this. However, this implies that the method has not identified the actual failure cause in its list of possible causes, as the overall cause should be present in one possibility.

Information from fuzzy FTA and uncertainty along with imprecision of data is used by Yang *et al.* [34] in the creation of a diagnostic system. A knowledge of causal relationships in the operation process and system control is represented by a fault tree. Fuzzy logic is used to take into consideration possible uncertainty information and data. The knowledge base stores qualitative information from a fault tree in the form of production rules and quantitative information obtained. The diagnostic tool identifies any deviations in the system by comparing the system data with the production rules. The method is presented on a small system and would have to be extended to a larger example in order to show how effective it can be. Also, only AND and OR logic is present in the fault trees used in the analysis, therefore the method does not take into consideration component working states.

Dynamic fault trees provide special constructs for modeling sequential failure modes in addition to standard combinatorial gates in FTA. Assaf and Dugan have developed a method to evaluate the possible cost of diagnosing a given network system when it fails [35–37]. A dynamic fault tree is created to illustrate the system model and for use in the diagnosis. This fault tree is then analysed and diagnosis performed by Automatic Diagnosis based on Reliability Analysis (ADORA), a diagnosis tool [36]. ADORA obtains diagnostic importance factors for each component within the system along with the cost and diagnostic importance factors (diagnostic information per unit cost of testing). The cost and diagnostic importance factor results are then used to order tests to be carried out. The tests are chosen depending on the symptoms given from the system. This information is used by ADORA in order to create a diagnostic decision tree [37] - which is similar in structure to the sequential diagnostic tree - to be evaluated for obtaining the cost of performing a diagnosis and to identify the potential causes of failure. The method is only used on a small real system configuration, therefore investigations need to be conducted in order to find out how effective it is on a larger system.

2.2.5 Bayesian Networks

The diagnosis of a failure can be described in terms of reasoning of the relationships between cause-effect and/or fault-symptom within a system. A fault may be the result of a number of different symptoms, whereas a number of failures may be the cause of just one symptom within a system. In many cases a fault-symptom relationship is probabilistic rather than deterministic, therefore there may only be a probability of a symptom occurring for a given failure [38]. Probability theory is able to contend with uncertain knowledge or rules and fuzzy input data along with functional mappings and simple thresholds from a system for the application in system diagnosis. This is achieved through the use of tools such as Bayesian networks. A Bayesian network consists of a set of variables or 'nodes', each of which has a finite set of mutually exclusive states and a set of directed edges [39], as shown in Figure 2.5.

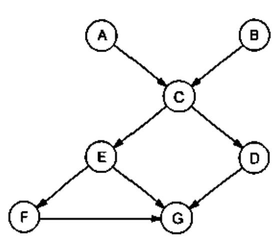


Figure 2.5: A simple Bayesian network

For each variable X that has parents $Y_1, \ldots, Y_n$ there exists a conditional probability table $P(X|Y_1, \ldots, Y_n)$. If a variable A has no parents then there would just be the probability $P(A)$. In figure 2.5 $P(A)$ and $P(B)$ are 'a priori' probabilities which must be specified. The other probabilities to specify are $P(C|A, B)$, $P(E|C)$, $P(D|C)$, $P(F|E)$ and $P(G|D, E, F)$. The information from the Bayesian network can be used to build a simple conditional probability table to indicate the probabilities of occurrence of failure.

It is often hard to specify all the necessary node probabilities and this has been identified as a difficulty when using Bayesian networks for fault diagnosis. Kirsch and Kroschel [38] addressed this problem. This is carried out by obtaining the probabilities through solving a series of non-linear equations developed from known probabilities. The method was found to be very complex even for the simplest of real world examples. Numerical methods were found to provide some solutions for solving parts of the general non-linear equation system, but more investigations were found to be required.

Wolbrecht *et al.* [40] have developed an approach that uses Bayesian networks for monitoring and diagnosis of a multi-stage manufacturing process. The methodology is demonstrated for the cap alignment process - the manufacturing of a product during which a cap is aligned to a base and joined together - for the identification of single and multiple failures. Monitoring of the system is performed on-line in real time to identify any sensor deviations and obtain a diagnosis as soon as possible to reduce system down-time.

A Bayesian network model is developed for each cap and base part that collectively represent the probabilistic relationships between inspection data, alignment position and alignment process components. A network is constructed with a set of nodes with causal relationships present between nodes. Each node also has an associated conditional and '*a priori*' probability. The part models are combined to generate a process model for the current overall system, which was implemented as a Visual C++ program. This is used to determine the '*a posteriori*' probabilities of the alignment process components using the observed data from the basic inspection points.

The real-time application allows failures to be detected on-line. In some cases once a fault is highlighted in a specific section this can be shut down and then the component is replaced or repaired. The precision of the diagnostic results with the approach is however dependent upon the accuracy of the configuration parameters. Large numbers of components in certain system sections have made the actual failure cause more difficult to ascertain, but at the very least the system still indicates that a failure has occurred. Another limitation is that the algorithm used to update the '*a posteriori*' probabilities will not completely scale to larger processes in its current state due to the large complexity.

Bayesian networks are applied to a power network system for fault diagnosis on a distribution feeder by Chien *et al.* [41] using expert system knowledge and historical data. From this information a Bayesian network is developed to model the causal relationships between the fault(s) in the system and observations from feeder outages. The expert system knowledge and historical data includes information records of the occurrence of past failures (such as date, time, location and equipment type), causes of incidents, along with records of prior and conditional probabilities. A Bayesian network for fault location was constructed and evaluated by an expert in order to indicate the suitability. This was then validated by comparing the results obtained for a selection of likely scenarios with those from the historical data. The method is only used for diagnosis of single failures in the system and needs further research in order to indicate the scalability to larger systems.

Application of Bayesian networks for use on the bleed air control system (BACS) of a Boeing 737NR aircraft is carried out by Paasch and Durgi [42] in order to develop a tool for troubleshooting a complex electromechanical system. The objective was to ascertain a fault in the system using a sequence of actions that minimised costs and resulted in a functioning system. The BACS has numerous sensors, which are used to indicate the presence of a deviation. During the diagnostic process the tool takes inputs from the sensors and is designed to suggest the most appropriate test to be carried out or the component to replace.

Due to the computational complexity and use of memory it was found to be impractical to apply Bayesian networks to obtain optimal troubleshooting and were not as accurate as decision analysis because of the assumption of conditional independence. They were however useful in the decision making process and can be used to improve the efficiency of the diagnosis procedure in an electro-mechanical system.

2.3 Summary of Rule-Based Diagnostic Systems

- A rule-based system uses a knowledge base developed by experts in order to diagnose any faults the system may encounter.
- The knowledge is collated into a set of rules, each drawn up in an 'IF-THEN' structure, the 'IF' giving a condition for the rule to be true and the 'THEN' being the consequence or action taken as a result.

- The rules can be used in any order as they are mutually exclusive.
- In general a depth-first forward chaining method is used in which the action taken in turn becomes the condition for the rule to be true until the chain ceases and the cause is obtained. This can be used in cases where a deviation has occurred and the cause is deduced by working through a subset of rules.
- A number of the systems use a method to obtain information and then use a set of rules to analyse this information to obtain a diagnosis.

2.4 Advantages of Rule-Based Diagnostic Systems

- A rule-based method is a structured approach that utilises the knowledge base of a system.
- In the event of any modifications made to the system the knowledge base can be easily up-dated, making this type of method straightforward to maintain.
- Rules can be implemented in any order.
- Each rule gives the user potentially more of an idea of the problem and how to solve it.
- The rules can be made to be as clear and concise as possible, allowing a simple root to diagnosis.

2.5 Disadvantages of Rule-Based Diagnostic Systems

- A rule-based system cannot learn from previous experience, unlike a human expert, therefore will not automatically modify its knowledge. Also it cannot up-date itself in the event of any modifications made to the system structure.
- In general a larger system will have a bigger set of rules that may make the diagnosis more complex and slower in obtaining a diagnosis.
- It could be difficult to provide coverage for all faults in the system with the method, depending on the complexity of the system it is being used on.

- Rule-based methods in general deal with finding single failures when in some situations there may be multiple faults exhibited.

2.6 Model-Based Diagnostic Systems

2.6.1 Introduction to Model-Based Systems

Model-based reasoning is a deductive process that uses a model of system behaviour to indicate how it should be working and compares this against what is actually being observed to highlight any abnormal activities. Figure 2.6 shows the relationship between the model of expected behaviour and the actual activity observed from the system.

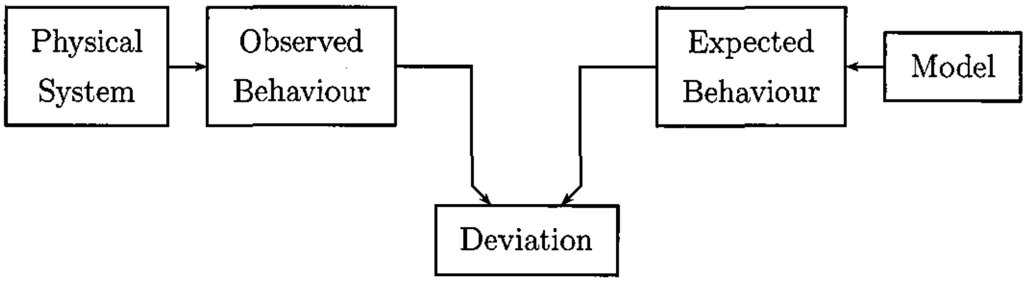


Figure 2.6: Diagnosis of system failure comparing expected and observed behaviour

The model of system behaviour is generated depending on the normal operating conditions. The observed system activity is then compared to that expected. Any difference between the two indicates that the system has deviated from its normal mode of operation, implying that a failure of some kind has occurred. When a deviation between the model and actual behaviour is encountered potential causes of failure are obtained and the most likely cause determined by performing system diagnosis.

The model is only an approximation to the real system, and so may not provide all possible information, (more details can be found in Shrobe [43]). In the majority of cases a model will not be able to be reused on a new system. Model-based reasoning works from the symptoms exhibited and traces the steps back to the underlying failure in the system.

2.6.2 Failure Modes and Effects Analysis (FMEA)

FMEA is an inductive or 'forward' qualitative reliability analysis tool that uses a 'what happens if' approach in order to identify potential system failure modes, their causes and the effect they can have on system operation. It provides a structured procedure for evaluating the severity of the failure modes for a system, subsystem or function. The knowledge of a system in a FMEA format has proved to be constructive in the development of diagnostic systems. The formation of a FMEA can however be very time consuming and human errors and inconsistencies are often likely as they are usually developed by hand. Also only single failures are normally considered in the analysis, which is a significant drawback.

Price and Taylor [44] and Price [2,45] demonstrated the use of automated FMEA to generate reports that could be used in a diagnostic tool, 'AutoSteve', for diagnosing multiple faults in systems using qualitative model-based reasoning. The tool is used by several automotive manufacturers for FMEA generation. A FMEA report is produced by obtaining the normal system behaviour and recording the operating functions. The possible failures that could occur can then be identified along with the functional behaviour of the system when each of these faults occur. The faulty and normal behaviour is compared and any discrepancies in the function are recorded in the FMEA report in order to indicate that a system has been affected by a failure.

Once the area in which a failure is situated has been located from the functional information the diagnostic system determines a list of possible component failures, which are ordered by likelihood. A series of tests, represented in the form of a diagnostic fault tree, can be employed to indicate whether the most likely cause is the actual fault. These will either show that this is the cause or will rule it out of the possibilities.

The information generated in the FMEAs can be verified by the engineers, which provides an extra beneficial level to analysis checking. A system can be divided into subsystems enabling the method to focus in on a smaller problem area. The method is also able to reduce the amount of time taken in drawing up a FMEA, which is normally developed by hand. The failures from the FMEA are only generated to a chosen degree of likelihood of occurrence - the system cannot generate failures containing four or more faults; therefore all possible outcomes for a system scenario may not be obtained. This is due to the amount of time taken to perform calculations. Also in some cases the tests carried out are not specific enough to obtain failures that develop gradually within a system. Building diagnostic trees using automated FMEA has decreased the construction time but this could still be improved if costs of tests were considered.

Atkinson *et al.* [46, 47] investigate the notion of automating FMEA for fault analysis on hydraulic system circuits. A model of the system is established and the behaviour collated in a library containing component models and their faults in a computer program. These can be used to simulate a required circuit. Each component model contains a description of its behaviour when in normal operation and when failed. Faults in the system are modelled by knowledge of the expected system behaviour and the possible failure modes for the system.

A circuit specification is input into the program in the circuit definition file, which will set up a new network of objects within the computer's memory in order to simulate this. Variables monitored within the system are pressure and flow. A qualitative simulation of the circuit is executed in order to determine the correct circuit operation. Faults can then be input into the simulation and once the faulty operation is located by the system sensors the possible effects are recorded in the FMEA. This is used to build up the affects that all faults in components in the circuit can have upon the system. Fault diagnosis is performed by inputting a fault into the system and allowing this to be detected and the FMEA to diagnose the cause and effects. Only single faulty components can be input into the program, therefore the method does not take into consideration multiple failures in the analysis.

A number of investigations carried out by Paasch *et al.* into development of mechanical system diagnosis have incorporated FMEA and fault trees [3, 4, 48–52]. The work is aimed at developing a method that can indicate how easily failures can be detected in a system so that improvements can be made to the diagnosability (the ease at which faults in a system are isolated [3, 4]). A method is presented by Ruff and Paasch [48] that uses structural functions to map visible indications of whether an operation is or is not being performed (performance measurements) to the components within the system (parameters) in order to gauge the system diagnosability. The method uses the relationships between the observed behaviour of the system and the potential causes of failure of the components. The normal operation of the system is determined at the conceptual phase of design and FTA is performed to identify any failed components for visible indications that have deviated from the expected system behaviour. The effects of these potential failures are collated into a FMEA to indicate the relationships between operations and components. Analysis is begun by the presence of abnormal behaviour, indicated as a discrepancy in the system model. The potential causes of failure are linked to this deviation using a set of rules to identify appropriate candidates. Clark and Paasch [49] extend this work to take into consideration unreliable failure indications and system components. The system modelling is carried out on conceptual, partially defined and defined mechanical systems.

Henning and Paasch [4] develop a diagnosability model that is initially built from system data in a FMEA and FTA in the same way as described by Ruff and Paasch [48]. The component-indication mapping methodology is also used to determine the relationships between components and observed system behaviour. The information from the FMEA and FTA is used to construct a series of matrices in order to describe the diagnosability model mathematically. These are then used in order to determine the rate at which components need to be replaced.

The work carried out by Henning and Paasch is extended by Mocko and Paasch [52] to include imperfect indications or sensors into the diagnostic model. The model is developed further using Bayes' formula in order to determine the truth of an event that is based on prior knowledge and current observations. A limitation to the research described is that only single failures are taken into consideration in the analysis and also indications are binary, therefore only yield a pass or fail whereas in reality they could be any value.

2.6.3 FTA

The notion of automating FMEA for fault analysis on hydraulic system circuits was described by Atkinson *et al.* in [46, 47]. Hogan *et al.* [53] use this program as a basis to automate the output of FTA. At the start of the analysis each possible failure in the system is assessed and a FMEA generated listing the local and global effects of the given fault. In order to generate an automated FTA a top level event is indicated for the system and then each FMEA containing this effect is investigated. Any faults found to have this effect are potentially the cause of the top level event in the system.

Multiple failures can be considered by injecting each failure separately into the system to allow the effect of each fault to be indicated. The problem with this strategy is that in some cases two failures input together may give different results to the same two failures input separately. The fault trees are analysed and a list of cut sets are obtained to indicate the potential failure causes for the system. The automated fault trees produced from the system do not contain success states and there is no provision for checking the potential causes of failure against working components.

Papadopoulos presents a model for on-line monitoring and diagnosis using fault trees to determine the causes of system failure [54–56]. The model consists of two parts, the first being a structural model that is developed from system information including the physical structure of the system, any subsystems present and the types of components within the system, their functions and possible failures. The second part of the model monitors the behaviour and contains knowledge of expected operations for the system and its subsystems. The model can identify any transitions made to deviated states in the system operation. Abnormalities are obtained through a Hazard and Operability (HAZOP) study. Identified failure transitions from the behavioural model correspond to the top events in the fault trees that are developed using the structural information. The model records the sequence in which failures happen and accounts for failures in their chronological order of occurrence within the fault trees.

NOT logic is excluded from the fault trees; therefore only component failures are taken into account to obtain a system diagnosis. As a result, some faults that occur simultaneously have required conflicting remedial procedures. This has been shown to cause unpredictable and potentially hazardous effects [56]. The work also indicated the need for better validation of the readings.

The use of fuzzy set theory as a diagnostic tool has been investigated by Gmytrasiewicz *et al.* [57]. Component failures within a system are diagnosed using the observed behaviour of 'fuzzy' or uncertain symptom information, which is stored in a fault tree structure. All gates within the fault tree are treated as symptoms and basic events are prospective failure modes. The method is divided into two parts. In the first part failure modes are diagnosed using causal reasoning - in order to establish the relationship between the cause of a failure and its effect - in the form of minimal cut sets that are obtained from the fault trees. Fuzzy set theory and fuzzy logic are used in order to account for any uncertainties or 'fuzziness' in measured symptoms from the system thus allowing for possible imprecision. Fault trees are generated for the observed system symptoms and an algorithm has been developed for diagnosing the failures that are represented by these trees.

In the second part, the actual failed components are identified based on the diagnosed failure modes using the list of possibilities obtained from the first part of the analysis. These are acquired by solving a series of equations generated from information in the first part of the analysis in order to relate the failure mode to the cause. The main limitation to this work is that the fault trees used only contain AND and OR logic, therefore there is no consideration of checking for consistency. The method has been tested on small systems, so further work involves testing the method on more complex examples.

Yangping *et al.* [58] have developed a method that utilises genetic algorithms, classical probability and characteristic fault diagnosis procedures for the diagnosis of multiple faults in nuclear power plants using the knowledge base of a system. Genetic algorithms are search routines based on Darwin's idea of 'survival of the fittest' [59]. They work with a population or 'colony' of candidate solutions or 'chromosomes' that are typically encoded as binary strings. The search is performed using a fitness function based around the actual function of the problem. It attempts to simulate the rules of the biological evolutionary process using reproduction (natural selection), crossover and mutation; the 3 main genetic operators within the algorithm.

A colony of strings are created in order to simulate the set of possible faulty component states within the system for a given set of sensor signals. The length of every string in the analysis is equal to the number of possible system failures, with '0's representing working components and '1's depicting failed components. The knowledge base is constructed from a combination of FTA and event tree analysis that considers only component failures. This information is used to calculate the fitness of each string and indicates how well each fits to the given system status. Diagnosis is terminated when either the pre-determined fitness value of a string is met, or the difference between the average fitness in several continuous colonies and the difference of strings in every colony is less than the pre-determined value. Therefore either the diagnosis is obtained or a number of possibilities within a certain range are obtained and need further analysis in order to get an overall result. There are a number of limitations with the described method. Genetic search is slow in obtaining solutions for large and complex systems and there can be problems determining when a global rather than a local diagnosis has been obtained. The initial strings are produced randomly, therefore if the character of a string is bad then this will be difficult to improve and obtain the actual failure cause. Work also needs to be carried out into obtaining a more effective fitness function for the system.

2.6.4 Digraphs and SDGs

Iri *et al.* [60] proposed a method for obtaining faults in chemical processing plants by applying graph theory for the diagnosis of single failures using SDGs to model system behaviour. The approach uses actual sensor readings obtained, which are compared to that expected in the system in order to indicate any deviations. The overall state of the system is determined by the state of each variable within it. These can be in one of three categories: high, normal and low that are defined by '+', '0' and '-' respectively. Therefore the system state is identified by a set of signs obtained from each state that are represented by nodes in the SDGs. The approach generates a cause-effect graph from the system SDG that contains nodes representing abnormal behaviour and edges illustrating fault propagation. Any nodes from the SDG exhibiting normal behaviour are excluded from the cause-effect graph. Process variables within the SDG are monitored and any deviations lead to the creation of the graph and then the potential causes of failure are determined through pattern propagation.

The approach was found to effectively identify single failures with single origins. The assumption of having systems that contain only single failures is however unrealistic. Multiple failures, although less likely than single failures, may still occur in systems. There could also be numerous areas of a system that indicate a deviation from a single fault, so this may also need to be taken into consideration. The research was extended by Iri *et al.* to take into consideration failed and working nodes in the failure identification [61] because it was found that eliminating the working nodes lead to a loss of information in some cases. This was carried out by developing an SDG with a partial pattern (signs are only placed on nodes where required). Within the analysis it has been assumed that there is only a single origin of system failure.

A SDG based algorithm for diagnosing multiple faults in systems was developed by Vedam and Venkatasubramanian [62]. A model of expected behaviour is determined by inspecting the system during normal operation. Failures can then be obtained through the identification of deviated process variables, for instance too much or too little mass flow at a certain point in the system. Single fault diagnosis is performed by identifying the propagations made through the process variables in the SDG. The strategy was modified to take into consideration multiple failures by identifying combinations of root nodes that lead to abnormal behaviour. A list of cut sets are obtained containing all possible failure outcomes. These are minimised so that each potential failure cause contains the smallest number of component failures such that if they all occur then so does the failure symptom. Analysis has been found to be computationally intensive and therefore multiple faults are explored only on an 'as needed basis' in order to reduce this. There is a problem of poor outcomes in certain system conditions, along with the identification of failures that cause conflicting arguments, which strengthens the need of some kind of consistency checking mechanism.

The directed graph or 'digraph' is similar to the SDG, but it uses numbers as well as signs on the arcs to indicate whether the cause or effect change is in the same or opposite directions respectively, and there are no signs associated with the actual nodes. Consider the example digraph shown in Figure 2.7. Edges in the digraph are depicted as lines and nodes as circles [63, 64].

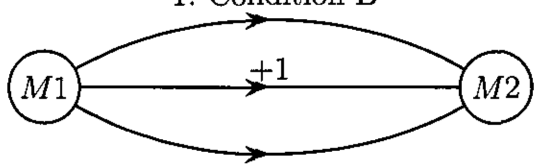


Figure 2.7: A simple digraph

Each node is labelled with the process variable and location number. The process variables in Figure 2.7 are mass flow rate at locations 1 and 2. Other possible process variables include pressure, temperature and sensor signals that can be represented by P, T and S respectively. $M1$ is an independent variable, and $M2$ is a dependent variable since the arrows on each edge are pointing from $M1$ to $M2$.

Each edge in the digraph is given a number indicating its associated gain that defines the relationship between two variables. The gain is signified using five numerical values: +10, +1, 0, -1, and -10. These represent the discrete categories strong high, moderate high, null, moderate low and strong low respectively. An edge that only consists of a number represents the relationship between two process variables that is usually true. Referring to Figure 2.7 the edge that has a gain of +1 is the normal edge. The other two edges are conditional, which indicates that each of these relationships can be true when the given condition is satisfied.

The same five discrete values +10, +1, 0, -1, and -10 are also used to indicate disturbances or failures in the process variables. A disturbance of zero shows that a variable has yielded its normal expected value. A value of 1 indicates a moderate disturbance in the system that can be controlled, and the sign determines whether this is above or below that expected. Larger disturbances are represented by an absolute value of 10 and cannot be put right by the system itself. A digraph can therefore be constructed to show the normal system function and the impact component failures and deviations from inputs can have.

In general a deviation in the dependent process variable caused by a deviation in the independent one is obtained by multiplying the disturbance from the independent variable by the gain. Referring to Figure 2.7, if the disturbance at $M1$ is $+1$, then $M2$ will also have a $+1$ deviation. The maximum deviation that can occur has an absolute value of 10, therefore if the gain was $+10$ and M1 $+10$ then this can only result in $+10$ at $M2$ also.

Ulerich and Powers [65] have developed a method for on-line hazard aversion and fault diagnosis for use in chemical process using digraphs and fault trees. A digraph model of the system is developed and used to generate fault trees to analyse the system faults. FTA is a reputable technique for use in the safety and reliability assessment of engineering systems. However, if two engineers were given the same system and undesired event then it would be most likely that they develop fault tree, comprising of different structures. Developing fault trees from digraphs provides an intermediate step that enables a more structured approach to be taken.

A digraph model is developed for the system. From this a causal fault tree describing the given identified disturbance is generated. This tree is expanded for fault detection to take into consideration consistency by adding verification gates to basic events to make sure that certain system conditions are met in order for the given event to possibly exist. Potential causes of failure are then obtained from the analysis in the form of a list of cut sets. The most likely cause is determined using real-time data. The fault trees may verify that certain system conditions are met, but they do not take into consideration components that are working successfully within the system. Further work is also required to investigate how the approach would scale to a larger system example.

Fault diagnosis using digraphs to model error propagation has been considered by Chessa and Santi [66] for systems containing single or multiple failures. A model of normal system behaviour is described by a set of sensor readings and compared to those actually occurring in order to indicate the presence of failure within the system. Sensors actively sound an alarm when an abnormal condition is indicated and remain silent when there is no failure at that particular location. This information is then used to analyse the digraph and obtain a set of potential failure sources, which are then tested in order to ascertain the actual failure cause.

Two separate algorithms were investigated: D-FAULTS and S-DIAG. Each algorithm searches the digraph for the location of the deviated sensors. The D-FAULTS algorithm could be used to diagnose a maximum of two failures at the same time within a system. Multiple failures could be identified by S-DIAG, which is a sequential diagnosis algorithm, but a drawback with this method is the time taken to obtain a diagnosis and repair the damage. This technique was further developed by Tu and Pattipati [67] to diagnose multiple failures in systems through the use of sensor alarms, but the method does not take into consideration faults that immediately affect the status of a system when they occur. System redundancy is also not addressed in the analysis.

The issue of diagnosing multiple failures in systems using digraphs is also addressed by Iverson and Patterson-Hine [68]. The use of an AND gate within the digraphs as depicted in Figure 2.8 enables both single and multiple failures to be identified and also provides a means of modelling system redundancy. Each AND gate can only have two inputs and one output, therefore to identify more than two failures multiple gates must be used.

The method uses a model of expected behaviour to highlight any deviations or failures at process variables (nodes). The digraph nodes are 'marked' true or false to identify whether a failure at that node has occurred. A marked deviation propagates through the digraph to the node's adjacent edges and determines other nodes that have failed as a result of the failure. If a node that is already marked is found the search ceases. A problem identified with this method is the computational time taken to identify the failures.

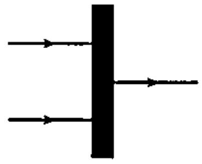


Figure 2.8: A digraph AND gate

Most recent investigations into developing a digraph fault diagnostic strategy have been carried out by Kelly and Bartlett [69,70]. The method developed uses digraphs to diagnose single and multiple faults in systems from observed sensor deviations. A digraph model is generated in which nodes representing system parameters are linked together with arcs that indicate the relationships between the nodes. System diagnosis is performed by comparing a set of sensor readings of actual behaviour to that expected in order to highlight any deviations. Failures are then obtained by back-tracing through the digraph. The method has been successfully applied to a fuel rig system. Investigations have yet to consider system redundancy and the possibility of improving results by increasing the number of sensors used in the analysis in order to 'home in' on more probable failures.

2.7 Summary of Model-Based Diagnostic Systems

- Model-based reasoning is a deductive process that uses a model of system behaviour to indicate how it should be working. Information regarding the system is obtained from the knowledge base for use in developing the model.

- The model of system behaviour is created and compared with that actually observed to highlight any abnormal activities. Any difference between the two indicates that the system has deviated from its normal mode of operation, implying that a failure of some kind has occurred.

- In some cases models can be automatically generated for fault detection.

- A model-based method can take into consideration what is occurring in the system as a whole rather than just through one test.

- The deviations obtained can provide a starting point as to the location and diagnosis of the failure.

2.8 Advantages of Model-Based Diagnostic Systems

- Information for a model can be supplied from the knowledge base built up from the system design or modified from existing data, therefore making the model easy and efficient to build.

- Model-based techniques use what is expected out of the system during its normal operation. It therefore utilises knowledge of the overall system in order to find out any deviations.

2.9 Disadvantages of Model-Based Diagnostic Systems

- Models are dependent on the data available from the system knowledge base and description. However, this information has become more accessible through the use of computers in the system development and during the design and manufacturing process stages.

- The model would have to be updated in the event of a modification in the system.

- In the majority of cases a model will not be able to be reused on a new system.
- There will always be minor discrepancies between the model and the physical system being diagnosed, although most of these will not cause any large effect on the results.
- It may be difficult to provide coverage of all types of fault within a system, but this will be dependent upon the structure.

Chapter 3

Fault Tree Methods

3.1 Introduction

However reliable a system is made it is likely to experience a failure of some kind during its life cycle. FTA is a deductive or 'backward' analysis technique that uses a 'what can cause this' approach in order to identify the causes of a system failure mode. The technique is widely used in the safety and reliability assessment of systems. The main objectives in the analysis procedure are to determine the possible causes of a specified system failure mode and then assess if the risk of failure is small enough to achieve an acceptable level of safety.

A system can be comprised of numerous components, each of which will at some point play a key part in its function. These components may also experience failure. A fault tree can symbolically represent the potential component failure events or events performed by an operator that could result in a particular system failure mode. This system failure mode is the 'TOP event', located at the top of the fault tree diagram, with branches below it leading to the possible causes of this undesired event. The probability for the occurrence of the TOP event may then be calculated if the probabilities for the component failure events are known. There may be more than one failure mode in a system, therefore a fault tree would need to be drawn for each.

3.2 Fault Tree Background

The first significant research into the reliability of systems was brought about by the aircraft industry wanting to improve the reliability of planes after the First World War. Initial investigations used trial and error techniques. Later developments were able to make use of data collected in order to make improvements and develop the reliability techniques used today.

The FTA concept was first introduced by H. Watson at Bell Telephone Laboratories in the early 1960s for use on the Minuteman missile system [71]. This was further developed during the 1960s and 1970s and is now one of the most widely used reliability modelling techniques.

3.3 Fault Tree Symbols

Fault tree diagrams are made up of 'gates' and 'events'. The two main types of event are intermediate and basic events. Each event in a fault tree is representative of an element of a system that can change state. Gates allow or restrict the passage of fault logic up through a fault tree, and indicate the causal relationships between the events that eventually lead to the occurrence of the top event.

Basic events in a fault tree are those where the limit of resolution has been reached, therefore the branch does not need to be developed any further. A basic event is depicted using a circle as shown in Table 3.1. Data for these events can used to formulate probabilities for the quantitative analysis of the fault tree. Another type of event is the house event, represented by a house symbol. These have probabilities of either 0 or 1, therefore can be used to turn parts of fault trees on and off in order to model two state events that do or do not occur. Intermediate events are represented in the fault trees using rectangles. This type of event can be further developed by a logic gate to other lower resolution events depending on causal relations. All event symbols are shown in Table 3.1.

The transfer in and out symbols are used to indicate the development of that particular part of the fault tree somewhere else in the diagram or on another page. This enables large fault trees to be broken down into sub-trees.

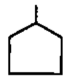
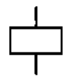
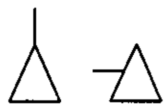
Event Symbol	Event Name and Meaning
	Basic Event
	House Event
	Intermediate Event (developed further by a gate)
	Transfer In and Out Symbols

Table 3.1: Event symbols in fault trees

A 'gate' is a logical operator that allows or restricts the passage of logic through a tree. The main types of gate in FTA are 'AND', 'OR' and 'NOT', shown in Table 3.2. These are used to combine events in the same way as the Boolean operators 'Intersection', 'Union' and 'Complementation' respectively. The 'VOTE' gate is another example gate. This allows the output event to occur if at least k inputs out of n occur and can reduce the overall size of the fault tree.

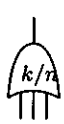
Gate Symbol	Gate Name	Casual Relation
	AND	The output event occurs if all of the input events occur. The number of inputs are ≥ 2.
	OR	The output event occurs if at least one of the input events occurs. The number of inputs are ≥ 2.
	NOT	The output event occurs if the input event does not occur.
	k/n VOTE	The output event occurs if at least k of the n input events occur. The number of inputs are ≥ 3.

Table 3.2: Main gate symbols in fault trees

3.4 Fault Tree Construction

The first step in the construction of a fault tree once information about components in the system has been gathered is to identify the system failure mode. If there can be more than one failure mode in a system then fault trees must be constructed for each. The specific system failure mode or 'top event' of the fault tree is defined and developed using branches leading to intermediate events. These intermediate events are redefined in terms of lower resolution events until all of the branches have been terminated by a basic event.

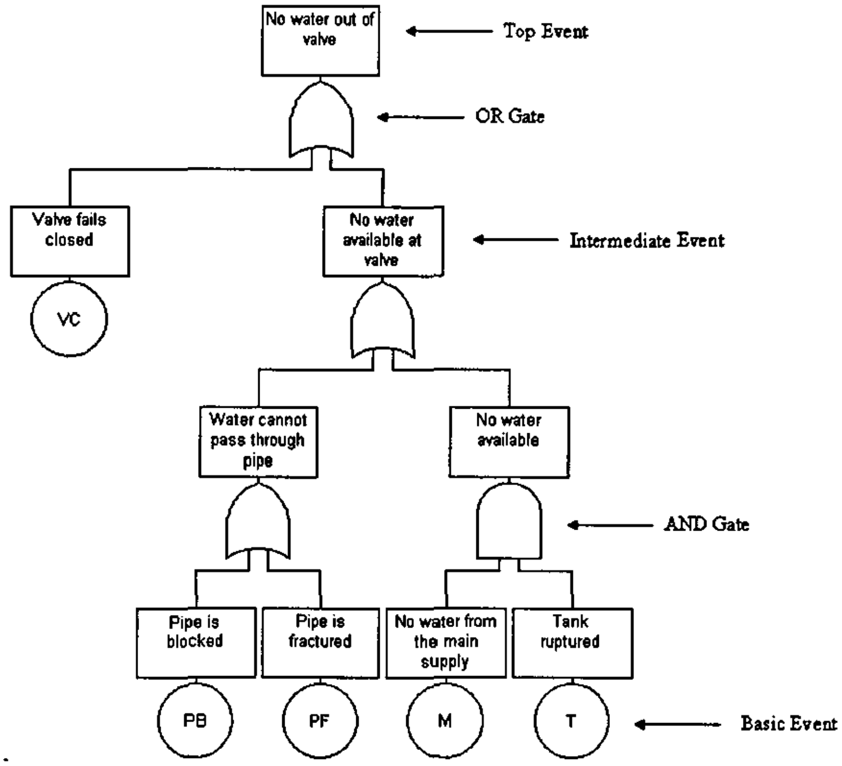


Figure 3.1: An example fault tree structure for the top event 'No water out of valve'

An example fault tree structure is shown in Figure 3.1 for the top event 'No water out of valve' for a simple system containing a tank, valve, pipe and water supply. The causal relationships in this fault tree are represented by three OR gates and an AND gate. The top event can occur either because the 'valve fails closed', resulting in a basic event, or because there is no water available at the valve, which is an intermediate event that can be developed further. Water may not be available because either it cannot pass through the pipe, or there is no water available to be drawn from the tank. 'Water cannot pass through the pipe' could be caused by the pipe being fractured or blocked. These are basic events that terminate the logical development. Finally, water may not be available because the tank has ruptured, AND there is no water available from an alternative main supply, which feeds the system.

There are two types of fault trees that can be constructed for analysis; coherent and non-coherent. A coherent fault tree is constructed from AND and OR logic, therefore only considers basic component failure events. A non-coherent fault tree expands this allowing the use of NOT logic, therefore the existence of both component failure and success events are taken into account.

Two types of analysis can be performed once a fault tree diagram has been constructed, these being 'qualitative' and 'quantitative'. Qualitative analysis is used to find all the possible causes of system failure by obtaining the basic component failure events that could contribute to the occurrence of the top event. Quantitative analysis is used to predict a system's failure parameters relating to both the availability and reliability in terms of the basic event failure probabilities.

3.5 Qualitative Analysis

3.5.1 Obtaining Minimal Cut Sets of Coherent Fault Trees

Qualitative analysis of a coherent fault tree can be used to logically express a system failure mode in terms of its basic component failure events. A potential cause of system failure can consist of an individual component failure event or a combination of failures. These can be defined as a 'cut set':

A cut set is a list of component failures such that if they all occur then the top event also occurs.

Large systems tend to be very complex, so in general they will produce a very large number of cut sets. Some of these, however, may contain events that are not necessary to cause the system failure mode. For example, the cut set $\{C, D\}$ would cause system failure if both basic events C and D were to occur. However, if there was another cut set $\{C\}$, then only the occurrence of C would be required to cause system failure, and whether D has failed or not would become irrelevant. This leads to the notion of a 'minimal cut set':

A minimal cut set is the smallest list of component failures such that if they all occur then the top event also occurs.

The order of a minimal cut set is the number of basic component failure events contained within the set. In general the lower order minimal cut sets are more likely to contribute to causing system failure. If two fault trees produce the same minimal cut sets then they are 'logically equivalent'.

The top event, T, of a fault tree can be expressed in terms of its minimal cut sets:

$$T = C_1 + C_2 + \ldots + C_{n_c}, \tag{3.1}$$

where, C_i $(i = 1, \ldots, n_c)$ are the minimal cut sets for the top event and the '+' represents logical OR.

Each minimal cut set can be made up of one or more basic component failure events. Therefore in general, a minimal cut set of order k can be expressed as:

$$C_i = X_1.X_2 \cdot \cdots . X_k, \tag{3.2}$$

where, X_i $(i = 1, \ldots, k)$ are the basic component failure events and the '.' is representative of logical AND.

Consider the following logical expression for the top event, T,

$$T = \mathrm{A} + \mathrm{B} + \mathrm{C.D}. \tag{3.3}$$

There are three minimal cut sets obtained for this top event; two of order one, $\{\mathrm{A}\}$ and $\{\mathrm{B}\}$, and $\{\mathrm{C}, \mathrm{D}\}$, which represents a combination of two failures.

3.5.1.1 Boolean Laws of Algebra

Minimal cut sets of a fault tree can be obtained by converting the logical expression for the top event, T, into its disjunctive normal or 'minimal sum-of-products' form [29]. This can be calculated using either the 'top-down' or the 'bottom-up' approaches for fault tree evaluation. These differ in where the expansion process is begun on a fault tree.

The approach most commonly used to obtain minimal cut sets is 'top-down'. The process begins at the top of the fault tree. This event is expanded by substituting in the Boolean events that appear lower down the tree until the expression only contains basic events.

Another approach that can be used to obtain minimal cut sets is 'bottom-up'. This approach uses the same substitution, expansion and reduction methods as in 'top-down', but in this case the process begins at the bottom of the fault tree and works up towards the top event. Only equations containing basic events are substituted into each gate.

Boolean laws of algebra are used to remove any redundancies from the expression so that it ends up in its simplified minimal form. Note that AND is represented by the product symbol '.' and OR by the summation sign '+'. (These are also equivalent to the union and intersection operations).

1. Commutative Laws:

$$A + B = B + A \tag{3.4}$$
$$A.B = B.A \tag{3.5}$$

2. Associative Laws:

$$(A + B) + C = A + (B + C) \tag{3.6}$$
$$(A.B).C = A.(B.C) \tag{3.7}$$

3. Distributive Laws:

$$A\cdot(B + C) = A.B + A.C \tag{3.8}$$
$$A + (B.C) = (A + B).(A + C) \tag{3.9}$$

4. Identities:

$$A + 1 = 1 \tag{3.10}$$
$$A + 0 = A \tag{3.11}$$
$$A.1 = A \tag{3.12}$$
$$A.0 = 0 \tag{3.13}$$

5. Idempotent Laws:

$$A + A = A \tag{3.14}$$
$$A.A = A \tag{3.15}$$

6. Absorption Laws:

$$A + A.B = A \tag{3.16}$$
$$A.(A + B) = A \tag{3.17}$$

7. Complementation:

$$A + \overline{A} = 1 \tag{3.18}$$

$$A.\overline{A} = 0 \tag{3.19}$$

$$\overline{(\overline{A})} = A \tag{3.20}$$

8. De Morgan's Laws:

$$\overline{A}.\overline{B} = \overline{(A + B)} \tag{3.21}$$

$$\overline{(A.B)} = \overline{A} + \overline{B} \tag{3.22}$$

3.5.1.2 Example of Obtaining Minimal Cut Sets

The top-down approach is now illustrated using the fault tree in Figure 3.2.

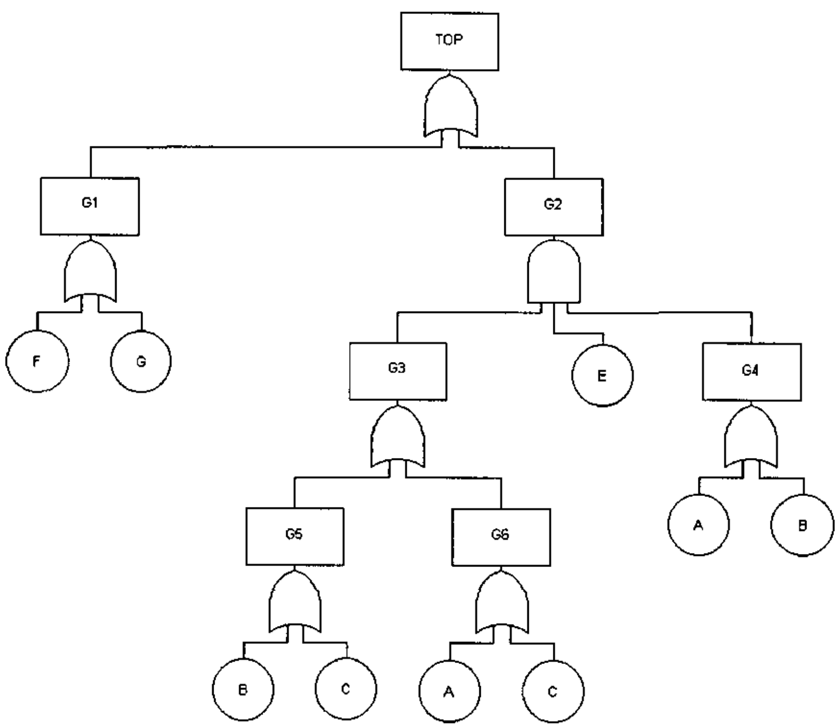


Figure 3.2: An example coherent fault tree

The process begins by starting at the top gate, 'TOP' in the fault tree. This is an OR gate with two inputs - two gates G1 and G2.

The top event, TOP, can be expressed as:

$$TOP = G1 + G2. \tag{3.23}$$

Gates G1 and G2 can be written as:

$$\begin{aligned} G1 &= F + G, \\ G2 &= G3.E.G4. \end{aligned}$$

These can be substituted into the top event from Equation 3.23:

$$TOP = F + G + G3.E.G4. \tag{3.24}$$

Gates G3 and G4 can be written as:

$$\begin{aligned} G3 &= G5 + G6, \\ G4 &= A + B. \end{aligned}$$

Therefore the top event, TOP in Equation 3.23 becomes:

$$TOP = F + G + (G5 + G6).E.(A + B). \tag{3.25}$$

Gates G5 and G6 can be written as:

$$\begin{aligned} G5 &= B + C, \\ G6 &= A + C. \end{aligned}$$

Substituting these into the top event gate in Equation 3.23 gives,

$$TOP = F + G + ((B + C) + (A + C)).E.(A + B). \tag{3.26}$$

Removing the brackets in the summations gives:

$$TOP = F + G + (B + C + A + C).E.(A + B). \tag{3.27}$$

Expanding Equation 3.27 gives,

$$TOP = F + G + B.E.A + C.E.A + A.E.A + C.E.A + B.E.B + C.E.B + A.E.B + C.E.B. \tag{3.28}$$

Using the Idempotent Laws, $A + A = A$ and $A.A = A$ (Equations 3.14 and 3.15), the expression for TOP can be simplified to:

$$TOP = F + G + B.E.A + C.E.A + E.A + B.E + C.E.B + A.E.B. \tag{3.29}$$

Now, using the Associative Law, $A.(B.C) = (A.B).C$ (Equation 3.7) and also the Absorption Law, $A + A.B = A$ (Equation 3.16) gives,

$$TOP = F + G + A.E + B.E. \tag{3.30}$$

This is the minimal disjunctive normal or 'sum-of-products' form. There are four minimal cut sets obtained, two of order one and two of order two. These are $\{F\}$, $\{G\}$, $\{A, E\}$ and $\{B, E\}$.

3.5.2 Use of NOT Logic

The fundamental types of gate used in FTA are 'AND', 'OR' and 'NOT'. A fault tree is said to be non-coherent if NOT logic is used in the structure. A system failure mode in this case can consist of individual basic component failure or working events, or a combination of these events. These can be defined as an implicant set:

An implicant set is a list of component failures and working states such that if they all occur then the top event also occurs.

A prime implicant set contains a list of events that are both sufficient and necessary to cause the top event:

A prime implicant set is the smallest list of component failures and working states such that if they all occur then the top event also occurs.

The use of NOT logic in fault trees for system quantification can increase the complexity of the analysis and provide only a small amount of extra information about system behaviour. Also, from a logical point of view, the implication is that a working component could contribute to the cause of system failure, which is an irrational argument. A system could be functioning but contain one or more component(s) that have failed. The argument is that repairing this/these component(s) could cause the system to fail. There are therefore a number of problems when using NOT logic in an analysis.

However, a system that can perform more than one task can benefit from the use of NOT logic to include the working states of components, as shown in Andrews [72]. Its use is also important in Event Tree Analysis [73] and since it provides a more complete description of the causes of system failure it is expected to play an important role in the use of fault trees for diagnostic purposes.

3.5.3 Evaluating Prime Implicants of Non-Coherent Fault Trees

3.5.3.1 Obtaining Prime Implicants

The first step in evaluating a non-coherent fault tree is to identify its prime implicants. These can be obtained by restructuring the fault tree using De Morgan's Laws (see Equations 3.21 and 3.22) so that any NOT logic is pushed down the tree resulting in complemented basic events. Consider the non-coherent fault tree shown in Figure 3.3.

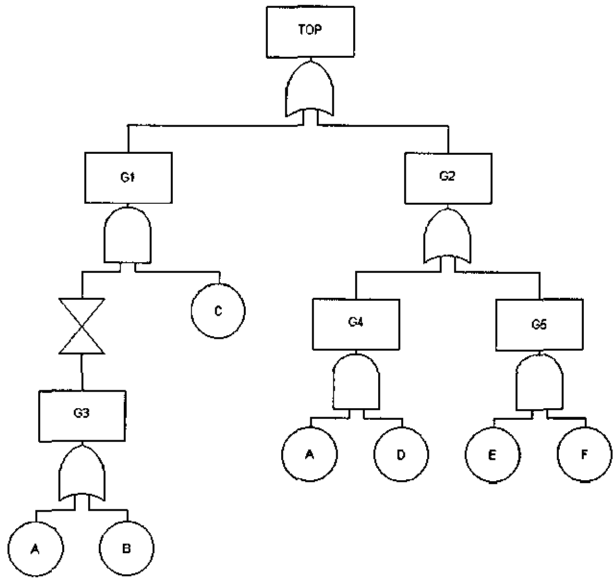


Figure 3.3: An example non-coherent fault tree

De Morgan's Laws can be applied to gate G3 in Figure 3.3 to give, $\overline{A+B} = \overline{A}.\overline{B}$. The equivalent fault tree obtained using De Morgan's Laws is shown in Figure 3.4:

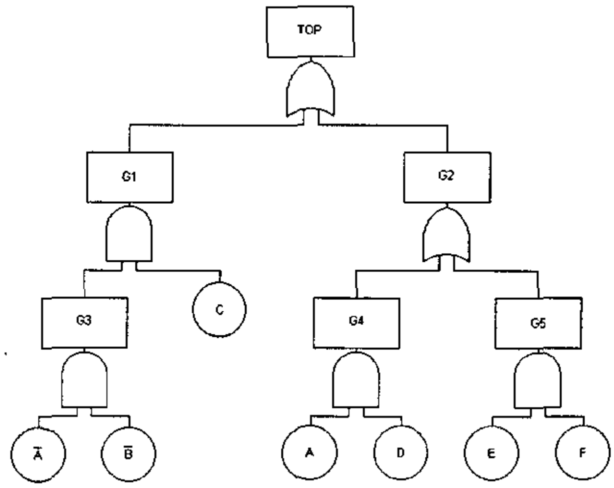


Figure 3.4: Equivalent non-coherent fault tree to that in Figure 3.3

The top-down approach can now be applied to the fault tree in Figure 3.4. The top event 'TOP' can be expressed as:

$$\text{TOP} = \text{G1} + \text{G2}.$$

Gates G1 and G2 can be re-written as:

$$\begin{aligned} \text{G1} &= \text{G3}.C \qquad && (\text{G3} = \overline{A}.\overline{B}) \\ \text{G1} &= \overline{A}.\overline{B}.C && \\ \text{G2} &= \text{G4} + \text{G5} && (\text{G4} = A.D) \\ & && (\text{G5} = E.F) \\ \text{G2} &= A.D + E.F. && \end{aligned}$$

Therefore, the top event TOP is:

$$\text{TOP} = \overline{A}.\overline{B}.C + A.D + E.F. \tag{3.31}$$

Since this is in minimal form three prime implicant sets - $\{\overline{A}, \overline{B}, C\}$, $\{A, D\}$ and $\{E, F\}$ - can be identified.

3.5.3.2 The Consensus Law

The expression for the top event given by Equation 3.31 has not, however, identified all of the possible prime implicant sets for this example. The top event could also be caused by component B not failing along with components C and D failing without considering the state of component A. This therefore gives a fourth prime implicant for this example. The additional possibility can be obtained using the Consensus Law:

$$XY + \overline{X}Z = XY + \overline{X}Z + YZ. \tag{3.32}$$

Applying the Consensus Law to the example in Figure 3.4, the first prime implicant in the top event structure (see Equation 3.31) contains $\overline{A}$ and the second contains A. The Consensus Law indicates that regardless of the state of A the top event could occur if $\overline{B}.C.D$ occurs. Therefore the consensus of $\overline{A}.\overline{B}.C + A.D$ is $\overline{B}.C.D$. The top event structure in Equation 3.31 can now be written as:

$$\text{TOP} = \overline{A}.\overline{B}.C + A.D + E.F + \overline{B}.C.D. \tag{3.33}$$

The Consensus Law should be applied to each pair of prime implicants containing a normal and negated state for the same basic component. There are no other such cases in this particular example. This law can be applied easily to small fault trees but application can become very complex when dealing with large fault trees.

3.5.3.3 The Coherent Approximation

Analysis of a non-coherent fault tree will in general produce more prime implicants than the number of minimal cut sets identified for the equivalent coherent fault tree. Also, the prime implicants obtained are normally of a higher order than for minimal cut sets as both component failure and working states are taken into consideration. This therefore can make the analysis of a non-coherent fault tree a more complex process and significantly heavy on computer processing power.

In order to reduce the complexity of the problem a coherent approximation can be taken during qualitative analysis of a system by assuming that any of the working states in the prime implicants are true (so have a probability of one). Any working states from the prime implicants can therefore be removed resulting in a list of cut sets. These can then be minimised to give a list of the failure events that cause the top event. Therefore a coherent approximation can be obtained for the top event in the example in Figure 3.4:

$$\begin{aligned} \text{TOP} &= \overline{A}.\overline{B}.C + A.D + E.F + \overline{B}.C.D, \\ \text{TOP} &\approx C + A.D + E.F + C.D, && \text{(removing working states)} \\ \text{TOP} &\approx C + A.D + E.F. && \text{(minimising)} \end{aligned}$$

Three minimal cut sets are obtained from the analysis after taking the coherent approximation and using Boolean reduction: $\{C\}$, $\{A, D\}$ and $\{E, F\}$. These are the potential causes of failure for the top event. In large fault trees the usage of the coherent approximation reduces the logic expression.

Notice that in performing the coherent approximation the extra term identified from the Consensus Law disappears from the analysis once Boolean reduction has taken place on the cut sets. Only the component failure events obtained from the top event will be required for the purpose of this study. Therefore the Consensus Law will not be used in any further work carried out.

3.6 Quantitative Analysis

Quantitative analysis is used to predict a systems failure parameters relating to both the availability and reliability in terms of the basic event failure probabilities. The probability and frequency for a top event is used along with the analysis of component or minimal cut set importance in order to gain a greater understanding of the system.

The original methodology for fault tree quantification is Kinetic Tree Theory developed by Vesely [74]. It allows time-dependent analysis in system evaluation and plays a key part in many of the commercial FTA packages. There are however a number of limitations in Kinetic Tree Theory resulting in the use of approximations in the analysis of top event quantification.

3.6.1 Maintenance Policies

The way a component is maintained can have a significant impact on its unavailability. Three different types of maintenance policy - no repair, unscheduled maintenance and scheduled maintenance - are discussed in the following sections.

3.6.1.1 No Repair

In this case repairs cannot be carried out and once a component is failed it will remain so. This type of situation is appropriate for remote controlled systems such as satellites, and on 'one-shot' machines, for example spacecraft.

For constant failure rate devices the system unavailability, $Q_{SYS}(t)$ is defined as:

$$Q_{SYS}(t) = F(t) = 1 - e^{-\lambda t}, \tag{3.34}$$

where λ is the *conditional failure rate* (the probability that a component fails per unit time at t given that it was working at time t and at $t = 0$). As time t increases the system unavailability tends to 1 ($t \to \infty$, $Q_{SYS}(t) \to 1$).

3.6.1.2 Unscheduled Maintenance

Repairs in this case are carried out as soon as a failure is detected in the system. Unscheduled maintenance is used for components that are continuously being monitored or on systems where a failure will become apparent because it causes a noticeable change in how the system is functioning. The time to repair a failure in this case does not include detection time.

For constant failure and repair rate devices,

$$Q_{SYS}(t) = \frac{\lambda}{\lambda + \nu}(1 - e^{-(\lambda+\nu)t}). \tag{3.35}$$

For unscheduled maintenance, as $t \to \infty$, $Q_{SYS}(t) \to \frac{\lambda}{\lambda+\nu}$.

3.6.1.3 Scheduled Maintenance

Maintenance or inspection takes place at fixed, scheduled time intervals. This type of maintenance is used in standby systems or safety protection systems that are not operated all the time. A failure in the system will not become apparent until a maintenance inspection is carried out. The time a system is shut down during scheduled maintenance will be dependent upon whether any failures are detected and if so how much time is required to repair it.

The unavailability of the system is:

$$Q_{SYS}(t) = 1 - e^{-\lambda[t-(n-1)\theta]}, \tag{3.36}$$

where, $(n-1)\theta \leq t \leq n\theta$, θ is the inspection interval and $n = 1, 2, \ldots$, is the number of inspections. The system is inspected at intervals of θ time units.

The average unavailability is:

$$Q_{AV} = \lambda\left(\frac{\theta}{2} + \tau\right), \tag{3.37}$$

where the inspection period is usually greater than the mean repair time, $\theta >> \tau$.

3.6.2 Top Event Probability

The probability of the top event, T, is also known as the system unavailability, $Q_{SYS}(t)$. There are several methods that can be used to calculate the top event probability of a fault tree. These include the Structure Function Method [29], Shannon's Theorem [75] and the Inclusion-Exclusion Expansion Principle. The inclusion-exclusion expansion principle will be described here.

3.6.2.1 The Inclusion-Exclusion Expansion Principle

The inclusion-exclusion expansion principle is the method utilised for calculating the top event probability. This approach may be used on fault trees that contain repeated events and can be directly obtained from the minimal cut sets. The top event in a fault tree will occur if at least one of the minimal cut sets exist.

Consider a fault tree that has n_c minimal cut sets C_i, where $i = 1, \ldots, n_c$. The top event, T, in the fault tree occurs if at least one minimal cut set occurs. Therefore:

$$T = C_1 + C_2 + \ldots + C_{n_c}, \qquad T = \bigcup_{i=1}^{n_c} C_i. \tag{3.38}$$

Therefore using Equation 3.38 the top event probability is:

$$P(T) = P(C_1 + C_2 + \ldots + C_{n_c}) = P\left(\bigcup_{i=1}^{n_c} C_i\right) = Q_{SYS}(t). \tag{3.39}$$

Expanding this result gives the inclusion-exclusion expansion:

$$P(T) = \sum_{i=1}^{n_c} P(C_i) - \sum_{1=2}^{n_c}\sum_{j=1}^{i-1} P(C_i \cap C_j) + \ldots + (-1)^{n_c-1} P(C_1 \cap C_2 \cap \ldots \cap C_{n_c}). \tag{3.40}$$

If this expansion is evaluated fully it will give the exact probability of the top event.

For example, consider the following top event, TOP, constructed from four components a, b, c, d:

$$\mathrm{TOP} = \underbrace{\mathrm{a.b}}_{C_1} + \underbrace{\mathrm{a.c}}_{C_2} + \underbrace{\mathrm{c.d}}_{C_3}, \tag{3.41}$$

where, C_1, C_2 and C_3 are minimal cut sets. The top event, TOP, is given in Equation 3.41. The probability of the top event occurring can be written as:

$$Q_{SYS}(t) = \mathrm{P(TOP)} = \mathrm{P(a.b + a.c + c.d)}. \tag{3.42}$$

Using the inclusion-exclusion expansion in Equation 3.40 and letting $q_a = q_b = q_c = q_d = 0.1$, gives:

$$\begin{aligned} Q_{SYS}(t) &= \underbrace{[\mathrm{P(a.b) + P(a.c) + P(c.d)}]}_{\mathrm{FirstTerm}} - \underbrace{[\mathrm{P(a.b.c) + P(a.b.c.d) + P(a.c.d)}]}_{\mathrm{SecondTerm}} \\ &\quad + \underbrace{[\mathrm{P(a.b.c.d)}]}_{\mathrm{ThirdTerm}}, \\ &= [q_a q_b + q_a q_c + q_c q_d] - [q_a q_b q_c + q_a q_b q_c q_d + q_a q_c q_d] + [q_a q_b q_c q_d], \\ &= [0.01 + 0.01 + 0.01] - [0.001 + 0.0001 + 0.001] + 0.0001, \\ &= 0.03 - 0.0021 + 0.0001, \\ &= 0.028. \end{aligned} \tag{3.43}$$

Even though the inclusion-exclusion expansion yields an exact result for the system unavailability, evaluating each term can be very computationally intensive. The example shown contains only three minimal cut sets. Larger examples could have hundreds or thousands of minimal cut sets. This would make the evaluation of the inclusion-exclusion expansion very heavy on computer processing power, even with the capability of the fastest of modern day computers. Therefore, although an accurate result is obtained, evaluation of the full expansion is often impractical, so an approximation is required.

All terms in the expansion play a part in the convergence to the exact probability. However, as can be seen from the last but one line of Equation 3.43 each term is less significant than the one before it. The method adds odd numbered terms and subtracts even ones. Therefore, if the expansion is truncated on an odd number of terms an upper bound for the top event probability will be obtained, and on an even number will provide a lower bound.

3.6.2.2 Approximation Methods

There are three main approximation methods for calculating the top event probability: the lower bound, the rare event upper bound and the minimal cut set upper bound.

3.6.2.2.1 The Lower Bound

A lower bound, Q_{LB}, for the top event probability is obtained if the inclusion-exclusion expansion is terminated after an even number of terms. For example, using the first two terms gives:

$$\underbrace{\sum_{i=1}^{n_c} P(C_i) - \sum_{1=2}^{n_c}\sum_{j=1}^{i-1} P(C_i \cap C_j)}_{Q_{LB}} \leq Q_{SYS}(t). \tag{3.44}$$

3.6.2.2.2 The Rare Event Upper Bound

The rare event upper bound, Q_{RE}, for the top event probability contains just the first term of the inclusion-exclusion expansion. This is also known as the Rare Event Approximation because it is accurate if the component failure events are rare.

$$Q_{SYS}(t) \leq \underbrace{\sum_{i=1}^{n_c} P(C_i)}_{Q_{RE}}. \tag{3.45}$$

Note also that an odd number of terms in a bound will always result in an upper bound.

Therefore, the upper and lower bounds for $Q_{SYS}(t)$ are:

$$\underbrace{\sum_{i=1}^{n_c} P(C_i) - \sum_{1=2}^{n_c}\sum_{j=1}^{i-1} P(C_i \cap C_j)}_{Q_{LB}} \leq Q_{SYS}(t) \leq \underbrace{\sum_{i=1}^{n_c} P(C_i)}_{Q_{RE}}. \tag{3.46}$$

3.6.2.2.3 The Minimal Cut Set Upper Bound

The minimal cut set upper bound, Q_{MCSU}, is a more accurate upper bound to the exact solution. The top event will occur if at least one minimal cut set occurs. Therefore,

$$\begin{aligned} P(T) &= P(\text{At least one minimal cut set occurs}) \\ &= 1 - P(\text{No minimal cut set occurs}). \end{aligned} \tag{3.47}$$

In view of the fact that:

$$\begin{aligned} P(\text{No minimal cut set occurs}) &= P(\overline{C}_1.\overline{C}_2.\ldots.\overline{C}_{n_c}), \\ &\geq \prod_{i=1}^{n_c} P(\text{Minimal cut set } i \text{ does not occur}). \end{aligned}$$

(Equality occurs when all the minimal cut sets are independent).

The expression for $P(T)$ in Equation 3.47 can now be written as:

$$P(T) \leq 1 - \prod_{i=1}^{n_c} P(\text{Minimal cut set } i \text{ does not occur}).$$

Therefore, the minimal cut set upper bound, Q_{MCSU}, is:

$$Q_{SYS}(T) \leq \underbrace{1 - \prod_{i=1}^{n_c}(1 - P(C_i))}_{Q_{MCSU}}. \tag{3.48}$$

3.6.2.2.4 Relationships to the Exact Top Event Probability

The following expression illustrates the relationship between $Q_{SYS}(t)$ and its approximations.

$$\underbrace{\sum_{i=1}^{n_c} P(C_i) - \sum_{1=2}^{n_c}\sum_{j=1}^{i-1} P(C_i \cap C_j)}_{Q_{LB}} \leq \underbrace{Q_{SYS}(t)}_{Q_{EXACT}} \leq \underbrace{1 - \prod_{i=1}^{n_c} P(1 - P(C_i))}_{Q_{MCSU}} \leq \underbrace{\sum_{i=1}^{n_c} P(C_i)}_{Q_{RE}}.$$

3.7 Importance Measures

The contribution made by a component or minimal cut set to cause the top event is defined as its importance [29]. The importance analysis of a system is a sensitivity study that can identify weak areas, which is especially useful at the design stage.

Fault tree quantification using a measure of importance can be carried out if there is data known for the components. An importance measure will assign each component or minimal cut set with a numerical value from 0 to 1, where a 1 indicates the highest contribution to failure and 0 no contribution at all.

Importance measures can either be deterministic or probabilistic. Probabilistic measures can be broken down again into those that can be used in system availability (the fraction of the total time that a system (or component) is able to perform its required function) assessment and those in system reliability (the probability that a system will operate without a failure for a stated period of time under specified conditions) assessment.

3.7.1 Deterministic Measures

Deterministic measures can be used to assess the importance of a component to a system without taking into consideration the probability of occurrence of the component. An example of such a measure is the structural measure of importance. More details about this measure are given in Andrews and Moss [29].

3.7.2 Probabilistic Measures

Probabilistic measures of importance are in general of more use than deterministic measures when assessing practical reliability problems. These measures take into consideration the component failure probabilities and intensities, therefore providing more information about a system and its components.

Two examples of measures concerned with system unavailability used for assessing minimal cut set importance are the *Fussell-Vesely Measure of Minimal Cut Set Importance* and the *Fussell-Vesely Measure of Component Importance.* Again, more details about these and other probabilistic measures can be found in Andrews and Moss [29].

3.7.2.1 Fussell-Vesely Measure of Minimal Cut Set Importance

The Fussell-Vesely measure of minimal cut set importance, I_{C_i}, ranks the minimal cut sets rather than the components and is defined as the probability of occurrence of cut set C_i ($P(C_i)$) given that the system has failed. This measure of importance can be expressed as:

$$I_{C_i} = \frac{P(C_i)}{Q_{SYS}(q(t))}. \tag{3.49}$$

For example, if the minimal cut sets of the system are {a, b} and {c} then the corresponding importance is:

$$I_{C_{ab}} = \frac{q_{\mathrm{a}}q_{\mathrm{b}}}{q_{\mathrm{a}}q_{\mathrm{b}} + q_{\mathrm{c}} - q_{\mathrm{a}}q_{\mathrm{b}}q_{\mathrm{c}}}, \tag{3.50}$$

and,

$$I_{C_c} = \frac{q_{\mathrm{c}}}{q_{\mathrm{a}}q_{\mathrm{b}} + q_{\mathrm{c}} - q_{\mathrm{a}}q_{\mathrm{b}}q_{\mathrm{c}}}. \tag{3.51}$$

The advantages of using measures of importance are that it will enable the most likely cause of failure to be determined depending upon component unavailability in the event that there is more than one possible outcome. This will allow investigations to commence in the area with the most probable cause rather than having to go through each possible outcome to see if that is the failure.

3.7.2.2 Fussell-Vesely Measure of Component Importance

The Fussell-Vesely measure of importance, I_i, is defined as the probability of the union of the minimal cut sets containing i, given that the system has failed.

$$I_i = \frac{P(\bigcup_{k|i\in c_k} C_k)}{Q_{SYS}(q(t))}.$$

The results obtained by this importance measure are very similar to the rankings given by the criticality measure of component importance [29].

Using the same example as for the Fussell-Vesely Measure of Cut Set Importance in Section 3.7.2.1 gives:

$$I_{C_a} = \frac{q_{\mathrm{a}}q_{\mathrm{b}}}{q_{\mathrm{a}}q_{\mathrm{b}} + q_{\mathrm{c}} - q_{\mathrm{a}}q_{\mathrm{b}}q_{\mathrm{c}}}, \tag{3.52}$$

$$I_{C_b} = \frac{q_{\mathrm{a}}q_{\mathrm{b}}}{q_{\mathrm{a}}q_{\mathrm{b}} + q_{\mathrm{c}} - q_{\mathrm{a}}q_{\mathrm{b}}q_{\mathrm{c}}}, \tag{3.53}$$

and,

$$I_{C_c} = \frac{q_{\mathrm{c}}}{q_{\mathrm{a}}q_{\mathrm{b}} + q_{\mathrm{c}} - q_{\mathrm{a}}q_{\mathrm{b}}q_{\mathrm{c}}}. \tag{3.54}$$

3.8 Summary

- The fault tree method enables possible causes of a system failure mode to be presented in a failure logic diagram.
- There are two types of fault trees that can be constructed for analysis; coherent and non-coherent.
    1. A coherent fault tree is constructed from AND and OR logic, therefore only considers basic component failure events.
    2. A non-coherent fault tree expands on the coherent fault tree construction by allowing the use of NOT logic, therefore the existence of both basic component failure and success events are taken into account.
- Two types of analysis can be performed once a fault tree diagram has been constructed, these being 'qualitative' and 'quantitative'.
    1. Qualitative analysis is used to find all the possible causes of system failure by obtaining the basic component failure and success events that could contribute to the occurrence of the top event in the fault tree.
    2. Quantitative analysis is used to predict a system's failure parameters relating to both the availability and reliability in terms of the basic event failure probabilities.
- Measures of importance can be used to determine the most likely cause of system failure should there be more than one possibility.

3.9 Reasons for Further Research into a Model-Based Strategy Incorporating FTA

The following are a list of reasons why an approach that utilises the strengths of a model-based strategy incorporating FTA to perform fault diagnosis forms the basis for the research conducted in this project.

- Systems usually contain sensors and faults give out symptoms. A physical system can be used to develop a model of behaviour through the information from the sensor readings as described in Chapter 2. Expected behaviour can be determined along with possible deviations, which can be investigated further.

- Potential multiple failure locations could be identified through a model-based technique using the sensor readings within the system. Deviated readings from the sensors could potentially indicate a number of different faults.

- Fault trees can be drawn for each system failure mode as indicated within this Chapter. A system failure mode is identified through determining the reading from each sensor located within the system. A failure logic diagram can be drawn for each deviated reading. These can then be used to indicate the overall system status or 'scenario'.

- The fault tree logic is such that it would enable multiple failures (through the use of the AND gate) to be identified within a system when analysis is performed for a given scenario.

- The use of non-coherent fault trees, i.e. those that contain AND, OR and NOT logic may enable the successful component behaviour in the system to be taken into consideration. Any potential causes of failure that conflict with those working as expected could then be removed.

- There may be potential to use the information from sensors that are reading true to the system operating mode. These could be included by using success trees for those that are working as required.

- A check of consistency of results obtained against those parts of the system that are working is often not present in the methods reviewed. This check would potentially allow the non-deviated sensor readings to be included in the analysis.

Chapter 4

Application of Fault Tree Analysis for Fault Detection

4.1 Introduction

It is possible that system failures are not the result of one single fault. Therefore the ability to diagnose multiple faults is important in a successful fault detection system. This chapter introduces four fault tree based schemes for detecting faults or combinations of faults and discusses the efficiency of each method [76, 77]. The schemes described are applied to a simple water tank level control system to demonstrate their features.

4.2 The Simple Water Tank Level Control System

The simple water tank system is illustrated in Figure 4.1. It aims to maintain the level of water between two pre-determined limits. In the normal operating mode water flows out of the system through valve V2. The level control system monitors when water is flowing from the tank and then refills it from the main supply by opening valve V1 until the desired tank level is reached. If the amount of water in the tank reaches an undesired high level the control system will open the safety outlet valve V3 allowing the water an alternative route out of the tank. The overspill tray, located underneath the tank collects any spillages that may occur due to a failure in the system.

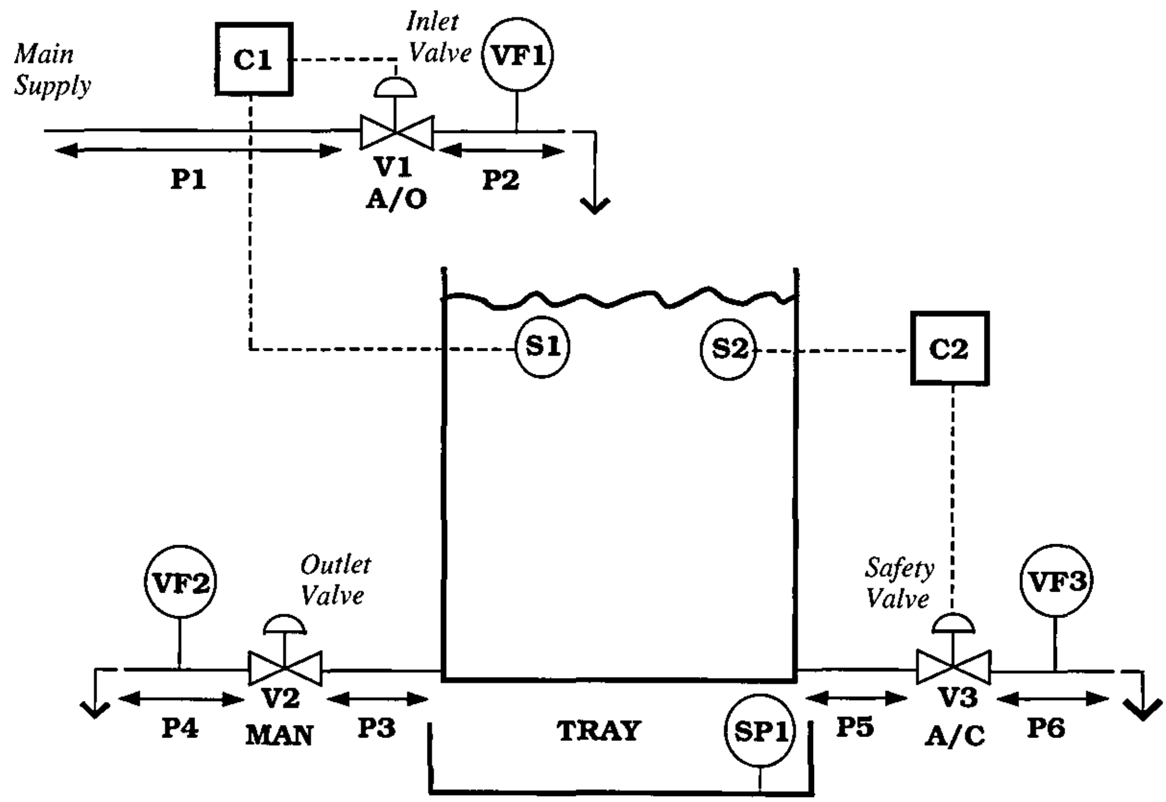


Figure 4.1: Water tank system

4.2.1 System Component Description

The water tank system shown in Figure 4.1 consists of three valves labelled V1, V2 and V3, two level sensors represented by S1 and S2, two controllers C1 and C2, and an overspill tray denoted TRAY. There are six sections of pipes identified by the labels P1 to P6.

V1 is an air-to-open (A/O) inlet valve controlled by C1. The level sensor S1 detects the height of the water in the tank. In the normal operating mode if the water in the tank falls below the required level (as indicated by the sensor S1), the controller C1 opens valve V1 allowing water into the tank. Conversely, if the water in the tank rises to the required level then C1 closes V1.

V2 is a manual (MAN) valve, controlled by an operator in response to demand. Finally valve V3 is an air-to-close valve (A/C) that operates as a safety valve controlled by C2. Normally this will only become operational when a component failure occurs that causes a very high level of water in the tank. A signal from S2 would cause the controller C2 to open valve V3 to reduce the level of water in the tank.

The overspill tray located beneath the tank collects water if the tank has ruptured, if water has leaked out through a crack or hole, or if the water level overflows from the top of the tank.

4.2.2 System Operating Modes

4.2.2.1 Volume Flow Rate and Overspill Tray Sensor Locations

The status of the system is determined using measurements provided by flow sensors situated next to each of the three valves in the system. The sensors are denoted by VF1, VF2 and VF3 for locations at V1, V2 and V3 respectively. These each detect the presence or absence of flow of water, which can be denoted as flow 'F', or no flow 'NF'. Initially to develop the features of each method it is assumed that these sensors are perfectly reliable. A fourth sensor denoted by SP1 is located in the overspill tray (TRAY) to indicate if any water has escaped from the tank. Its reading is interpreted as water 'W', or no water 'NW'. All these sensor locations are called the system observation points. 16 different potential scenarios are evident for the system and are listed in Table 4.1. In the early stages of analysis it was sufficient to investigate the four fault tree based diagnostic techniques using just these sensors.

Scenario	V1	V2	V3	TRAY
1	F	F	F	W
2	F	F	F	NW
3	F	F	NF	W
4	F	F	NF	NW
5	F	NF	F	W
6	F	NF	F	NW
7	F	NF	NF	W
8	F	NF	NF	NW
9	NF	F	F	W
10	NF	F	F	NW
11	NF	F	NF	W
12	NF	F	F	NW
13	NF	NF	F	W
14	NF	NF	NF	NW
15	NF	NF	NF	W
16	NF	NF	NF	NW

Table 4.1: System scenarios

4.2.2.2 System Operating Assumptions

A number of assumptions have been made regarding the operation of the system:

- The system is always initialised with the required level of water in the tank.
- In the ACTIVE operating mode it can be assumed that the flow rate into the tank through V1 has the capability to be the same as the flow out at V2 (which varies

depending on the height of water in the tank). Therefore the required water level in the tank can always be maintained when water is being drawn out of the system in this way.

- The areas of pipes P5 and P6 are larger than those of the other pipes in the system so that water can be drained quickly from the tank in the event of the level rising too high. Flow out of V3 therefore has the potential to be greater than flow in at V1.

- When a 'rupture' occurs in the tank (TR) this indicates that the liquid flow through the rupture will be greater than the maximum flow into the tank through valve V1. Therefore replenishment is not possible. It is assumed that a rupture can only occur in the bottom of the tank.

- Maximum flow into the tank through valve V1 will be greater than flow out through a 'leak' in the system (TL). A leak out of the system is also smaller than the maximum flow out at V2. For simplicity it is initially assumed that a leak will occur at the bottom of the tank.

4.2.2.3 ACTIVE and DORMANT Operating Modes

The system has two operating modes; these being 'ACTIVE' when the operator opens valve V2, or 'DORMANT' when V2 is closed. In the ACTIVE operating mode water is taken out of the system through valve V2 and the tank is refilled by water coming in through valve V1 from the main water supply. Water would not exit the system through valve V3 and there would be no water in the overspill tray. The sensor readings for the system when ACTIVE should be those given in scenario 4, Table 4.1. In the DORMANT operating mode the system is effectively on standby with all three valves remaining closed and the overspill tray empty. This should yield the sensor readings given in scenario 16, Table 4.1.

The expected sensor readings are those that, under steady-state conditions, represent the model of how the system should behave when ACTIVE and DORMANT respectively. Given that the system is in either the ACTIVE or DORMANT state any sensor readings that deviate from those expected are regarded as being indicative of some fault or faults within the system.

4.2.2.4 Possible Component Failures

In order to apply FTA to a system the faults that could occur for each of the system components need to be defined. Table 4.2 contains a list of possible component failures and their corresponding code.

System diagnosis is required in both the ACTIVE and DORMANT operating modes. Therefore these must also be represented in the fault trees. ACTIVE signifies the operator has attempted to open valve V2. DORMANT is used to indicate that the operator has tried to close V2. It should be noted that this is a two mode system and so only one of the variables ACTIVE or DORMANT can be true at any time.

Code		Component Failure	Code		Component Failure
PiB ($1 \le i \le 6$)	-	Pipe Pi is Blocked	CiFH ($1 \le i \le 2$)	-	Controller Ci Fails High
PiF ($1 \le i \le 6$)	-	Pipe Pi is Fractured	CiFL ($1 \le i \le 2$)	-	Controller Ci Fails Low
ViFC ($1 \le i \le 3$)	-	Valve Vi Fails Closed	TR	-	Tank Ruptured
ViFO ($1 \le i \le 3$)	-	Valve Vi Fails Open	TL	-	Tank Leaks
SiFH ($1 \le i \le 2$)	-	Sensor Si Fails High	NWMS	-	No Water from the Main Supply
SiFL ($1 \le i \le 2$)	-	Sensor Si Fails Low			

Table 4.2: Potential component failures

It has been assumed that a component can only be failed in one state at a time during the analysis, so for example pipe P1 being blocked and fractured at the same time (P1B.P1F) is an invalid result. This is similar for the valves, sensors, controllers and the tank.

A blockage in pipes P1 and P2 will stop flow into the system and in pipes P3 to P6 will cause no flow out. A fracture in pipe P1 will result in no flow into the system, but in P2 there will be flow in, and similarly a fracture in P4 or P6 will still result in flow out of the system. Finally, a fracture in P3 or P5 will cause flow out of the system, but this flow will not be registered on the volume flow rate sensors VF2 and VF3 respectively.

4.3 Sensor Deviation Models

In the application of FTA to system fault diagnostics a series of failure logic diagrams are produced representing the causes of any sensor readings at the observation points. These are developed in a fault tree in terms of the just component failure (coherent) and both component failure and success (non-coherent) conditions of the system operating state. The list of all possible sensor readings for the system is shown in Table 4.3.

Abbreviation		Sensor Readings	Abbreviation		Sensor Readings
FTV1	-	Flow Through Valve V1	NFTV1	-	No Flow Through Valve V1
FTV2	-	Flow Through Valve V2	NFTV2	-	No Flow Through Valve V2
FTV3	-	Flow Through Valve V3	WOST	-	Water in the Overspill Tray

Table 4.3: Sensor readings

Two other possible sensor readings for the system are 'no flow through valve V3' and 'no water in the overspill tray'. However these sensor readings would occur under normal operational conditions (i.e. without any failures occurring) in both the ACTIVE and the DORMANT operating modes.

4.3.1 Fault Tree Construction

Fault trees for the water tank system were initially constructed by hand for each of the sensor readings listed in Table 4.3. FaultTree+ is a fault tree software package that enables the user to construct and analyse fault tree diagrams [78]. The fault trees developed by hand were later verified by inputting them into FaultTree+ and checking the outcomes expected with those give from the software package. The construction of the coherent and non-coherent fault trees for the sensor reading NFTV2 is now described in Sections 4.3.1.1 and 4.3.1.2 respectively.

4.3.1.1 Coherent Fault Trees

4.3.1.1.1 No Flow Through Valve V2

The sensor reading 'No flow through valve V2' (NFTV2) is presented in the coherent fault tree in Figures 4.2 and 4.3. Referring to the water tank system illustrated in Figure 4.1 NFTV2 can occur either because V2 is closed or if there is no water available at V2. The valve could have failed closed (V2FC) or the system may be in a no flow phase and therefore in the DORMANT operating mode, represented by a house event, (DORMANT). This can be turned 'on' and 'off' (set to true or false) depending on the operational status.

Water may not be available at V2 either due to a problem stopping the flow out of the tank, or because there is no water in the tank. Flow could be restricted out of the tank due to a blockage in pipes P3 or P4 (P3B, P4B), or a fracture in P3 (P3F). No flow through V2 may also be caused by no flow out at valve V1 once the level of water in the tank becomes empty. This can be caused by a blockage in pipes P1 or P2 (P1B, P2B), a fracture in P1

(P1F) or no water from the main supply (NWMS). Additionally a failure in the V1 control loop could occur: V1 failing closed (V1FC), C1 failing high (C1FH) or S1 reading a high water level (S1FH)).

NFTV2 could also have been caused by there being a flow out at valve V3 that has drained the tank. However, if there is no water in the tank for this reason then there would also be no flow at V3 indicated at the VF3 sensor. If there is enough water to flow out at V3 then there will also be flow out at V2. Hence this potential cause would never become apparent. The failures that could cause flow out at V3 are therefore not included in this fault tree.

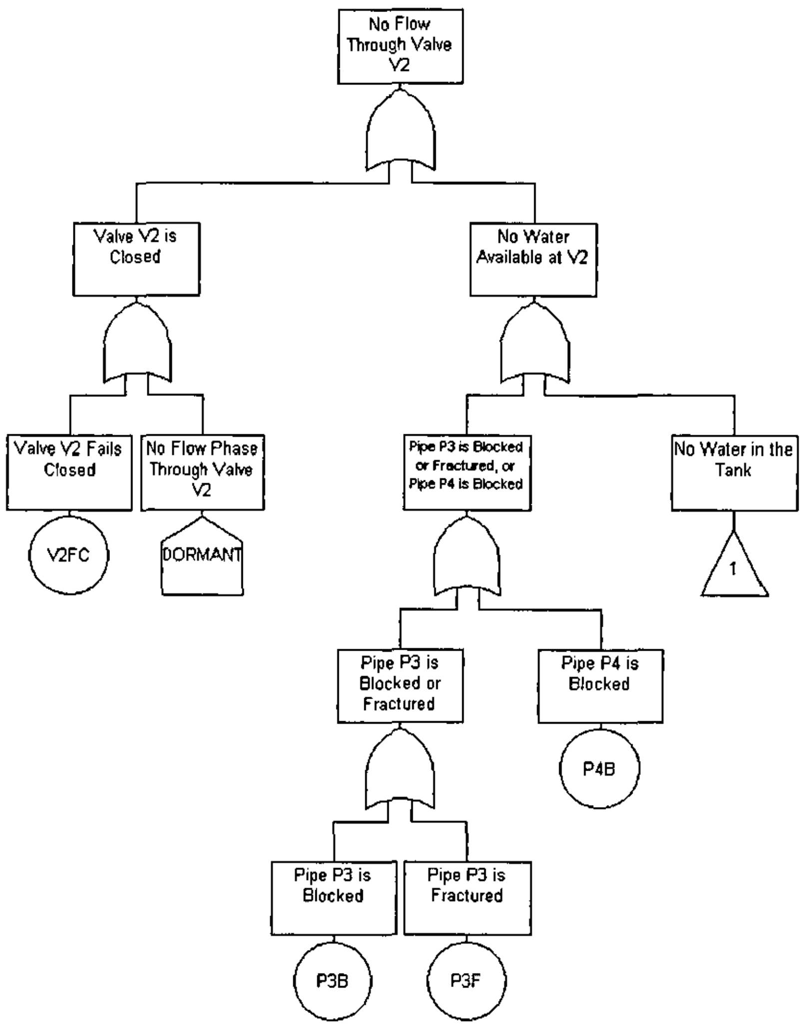


Figure 4.2: Coherent fault tree for no flow through valve V2

In total there are 13 possible causes of there being no flow at V2, and each of these are of single order. One of the results is a no flow phase through valve V2 (when the system is DORMANT) resulting in a non-failure. The remaining 12 are potential causes of failure for 'no flow through valve V2', and are listed in Table 4.4.

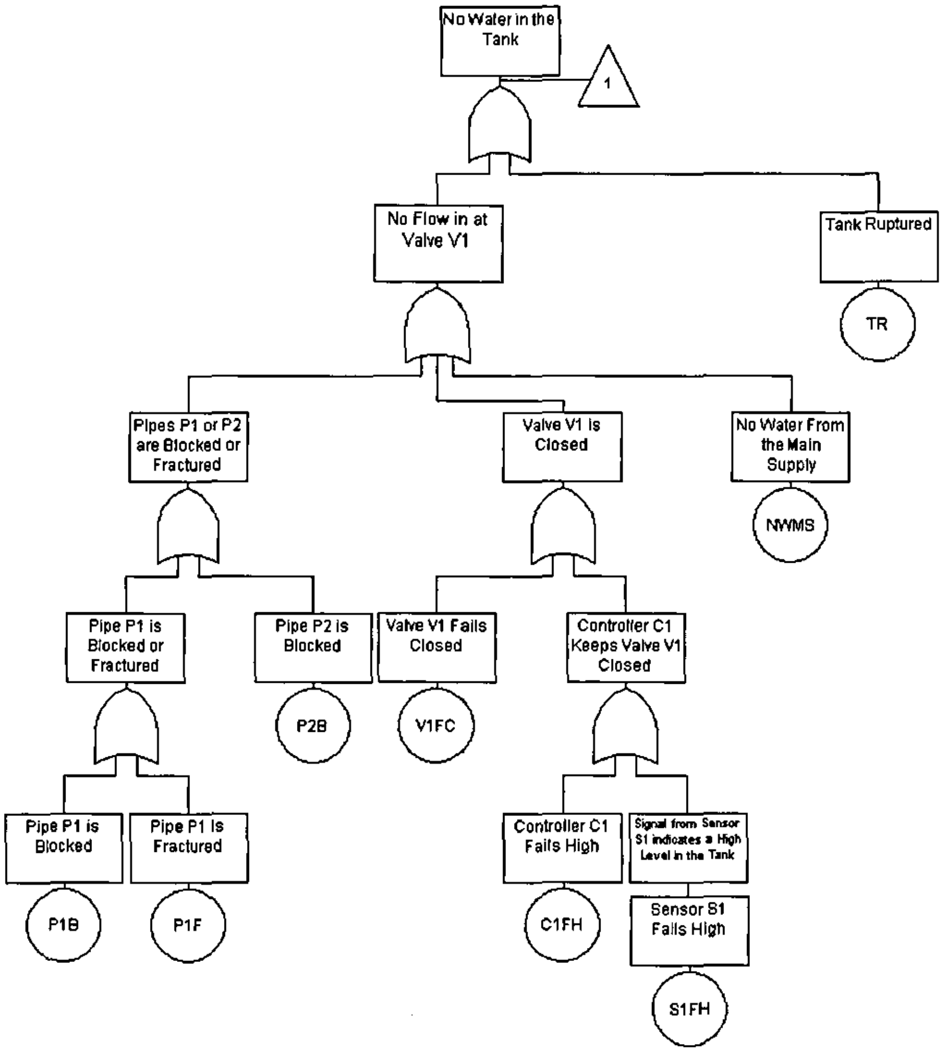


Figure 4.3: Coherent fault tree for no flow through valve V2 - transfer 1

Number	Potential Cause	Number	Potential Cause
1)	V2FC	7)	C1FH
2)	P3B	8)	S1FH
3)	P3F	9)	P1B
4)	P4B	10)	P1F
5)	TR	11)	P2B
6)	V1FC	12)	NWMS

Table 4.4: Potential causes of no flow through valve V2

4.3.1.1.2 Summary of Coherent Fault Trees

The coherent fault trees for the remaining sensor readings are shown in Appendix A. 'Flow through valve V1', shown in Figures A.1 and A.2 can occur either because the valve has spuriously opened, or if the level of water is lower than that required (as indicated by sensor S1 in the tank). This can be as a result of flow through valve V2 or V3, through the tank or via a pipe. There are 12 potential causes of failure for this reading, each of first order. The only possible potential cause of failure for 'flow through valve V2' is that this valve has failed open (V2FO). The other possibility shown in the fault tree in Figure A.3 is that the system is in a flow phase and is therefore in the ACTIVE operating mode, represented by the house event 'ACTIVE'. 'Flow through valve V3', shown in Figures A.4 to A.5 can occur either because the safety valve has spuriously opened, or if the water level is higher than required (as indicated by sensor S2 in the tank). A high level of water in the tank could be caused by flow in at V1 and no flow out at V2. If the system is ACTIVE then 15 potential causes of failure are obtained, 3 of single order and 9 second order. There are 6 potential causes if the system is in the DORMANT mode, all of first order.

The coherent fault tree for 'no flow through valve V1' (NFTV1) is shown in Figures A.6 and A.7. NFTV1 can occur either because there is no water available at V1 or if there is no flow out of the system at V2. Water may not be able to pass through V1 either because there is a problem restricting the flow, or because there is no water available. No flow out of the system at valve V2 would be the result of either the system being in the DORMANT operating mode or a failure causing V2 to remain closed. There are 10 possibilities in this case when the system is ACTIVE, all of order 1. Finally, 'water in the overspill tray' can occur either through a problem with the actual tank itself or because the level of water in the tank is high enough to spill over the sides, as illustrated in Figures A.8 to A.11. Problems with the water tank could have been caused either by a rupture resulting in a catastrophic system failure or due to a leak. A high level of water in the tank would be caused by flow into the system and no flow out of the system. There are 74 potential causes of failure when the system is ACTIVE, 2 of single order and 72 of order 3. In the DORMANT operating mode there are 20; 2 of order 1 and 18 of order 2.

4.3.1.2 Non-Coherent Fault Trees

The information described by the coherent fault trees in Section 4.3.1.1 can now be expanded to include everything in the system that is known not to have failed. The non-coherent fault trees show that the introduction of NOT logic significantly increases the amount of information known about the system behaviour.

4.3.1.2.1 No Flow Through Valve V2

Causes of the sensor reading 'no flow through valve V2' (NFTV2) are presented in the non-coherent fault tree in Figures 4.4 to 4.7.

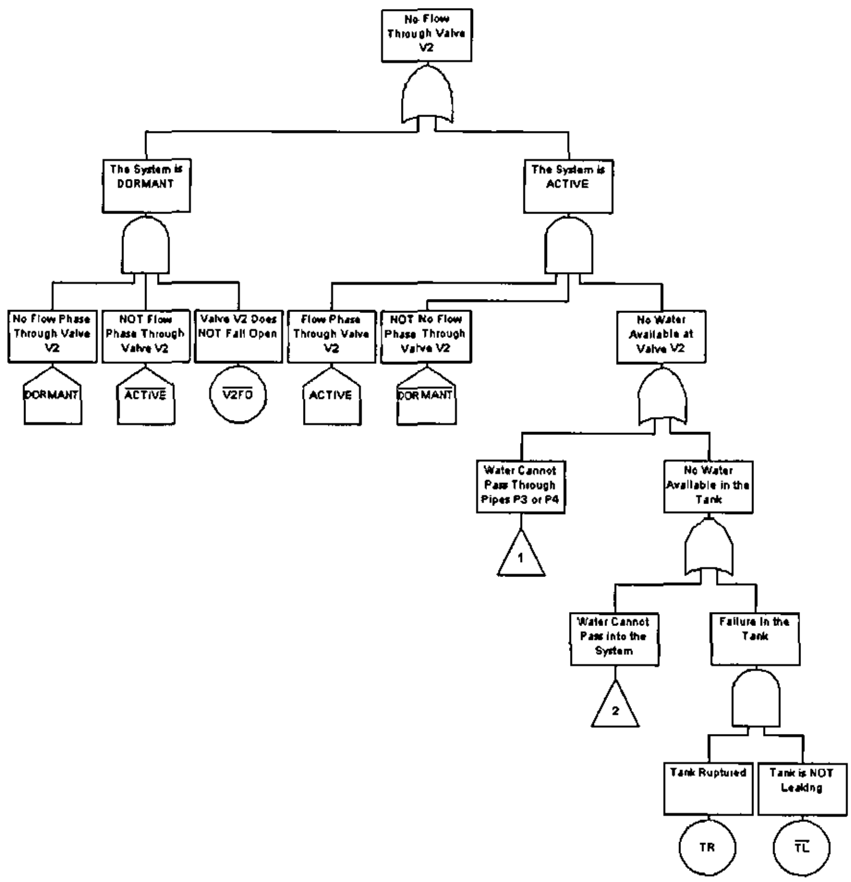


Figure 4.4: Non-Coherent fault tree for NFTV2

NFTV2 can be the result of there being a no flow phase at V2, so the system is in the DORMANT operating mode. In this case the system is not ACTIVE ($\overline{\text{ACTIVE}}$) and V2 cannot have failed open ($\overline{\text{V2FO}}$) (a bar over the basic event means 'NOT that event'). If the system is ACTIVE then this can be caused by no water being available at the valve. Therefore either water cannot pass through pipes P3 or P4, or there is no water available in the tank.

Water may not be available in the tank either because the water cannot pass into the system, or because of a rupture in the tank. If the tank has ruptured (TR) then it is not leaking ($\overline{TL}$).

'Water cannot pass through pipes P3 or P4', shown in Figure 4.5, can be caused by valve V2 failing closed (V2FC) and not open ($\overline{V2FO}$), by a blockage in either of the two pipes (P3B, P4B), or a fracture in P3 (P3F). If pipe P3 is blocked then it cannot be fractured ($\overline{P3F}$), and if fractured then it cannot be blocked ($\overline{P3B}$). Similarly for P4 if the pipe is blocked then it is not fractured ($\overline{P4F}$).

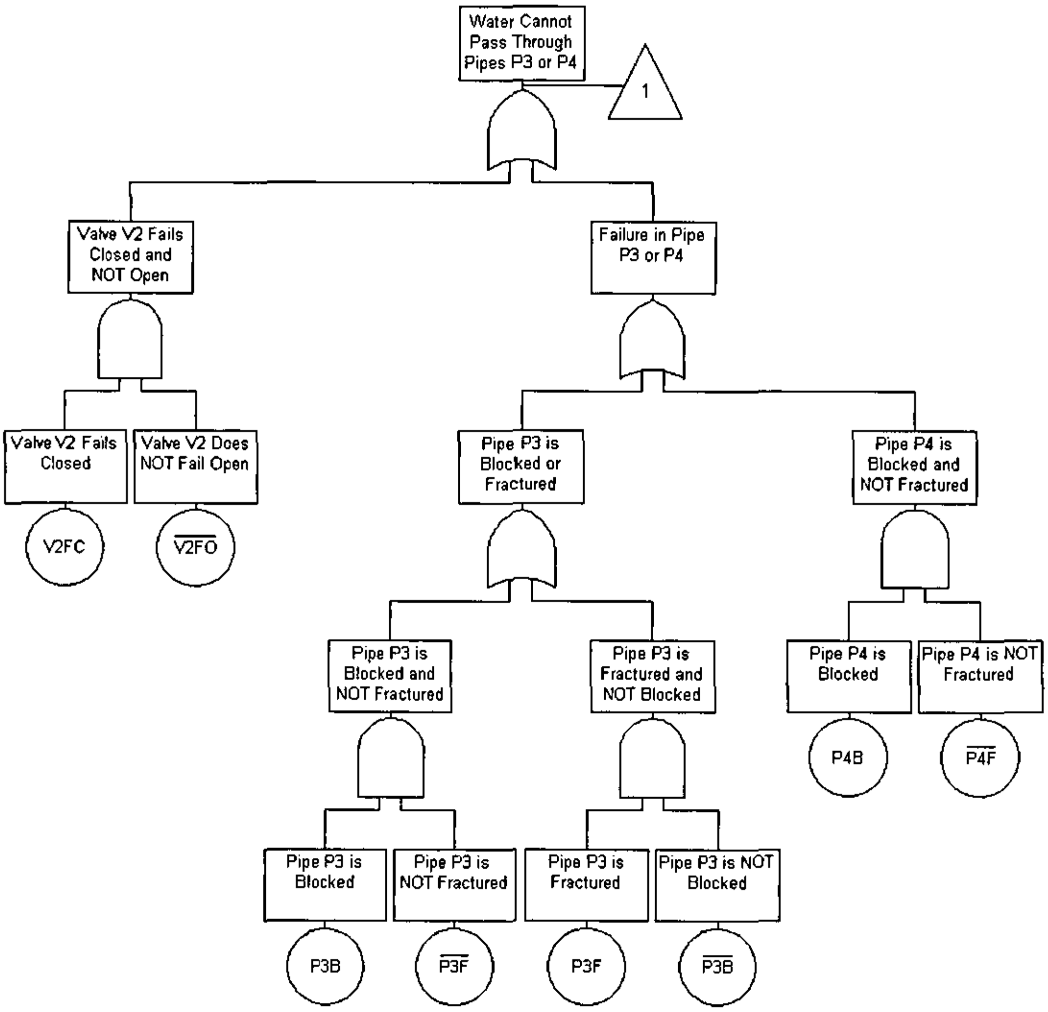


Figure 4.5: Non-Coherent fault tree for NFTV2 - transfer 1

Water may not be able to pass into the system at V1, causing no flow out at V2, as illustrated in Figure 4.6. No flow into the system at V1 may occur because water is unable to pass through the valve. This can be the result of either a problem restricting the flow, or because there is no water available. The flow may be restricted due to a blockage in pipe P1 or P2 (P1B, P2B), or a fracture in P1 (P1F). If pipe P1 is blocked then it cannot be fractured ($\overline{P1F}$), and if fractured then it cannot be blocked ($\overline{P1B}$). Similarly for P2 if the pipe is blocked then it is not fractured ($\overline{P2F}$). Finally water may not be available to the system because of a problem at the main supply (NWMS).

Water will not be available at the valve if it is closed, or because water is not able to pass through, as shown in Figure 4.7 . Valve V1 could be closed if controller C1 has failed high (C1FH), sensor S1 has failed reading a high level of water in the tank (S1FH), or if the valve itself has failed closed (V1FC). If V1 has failed closed then it has definitely not failed open ($\overline{V1FO}$). If C1 has failed high then it cannot have failed low ($\overline{C1FL}$) and V1 has not failed open. Finally if S1 has failed reading a high level of water in the tank then to cause no flow into the system it cannot be reading low ($\overline{S1FL}$), C1 cannot be low and V1 not open.

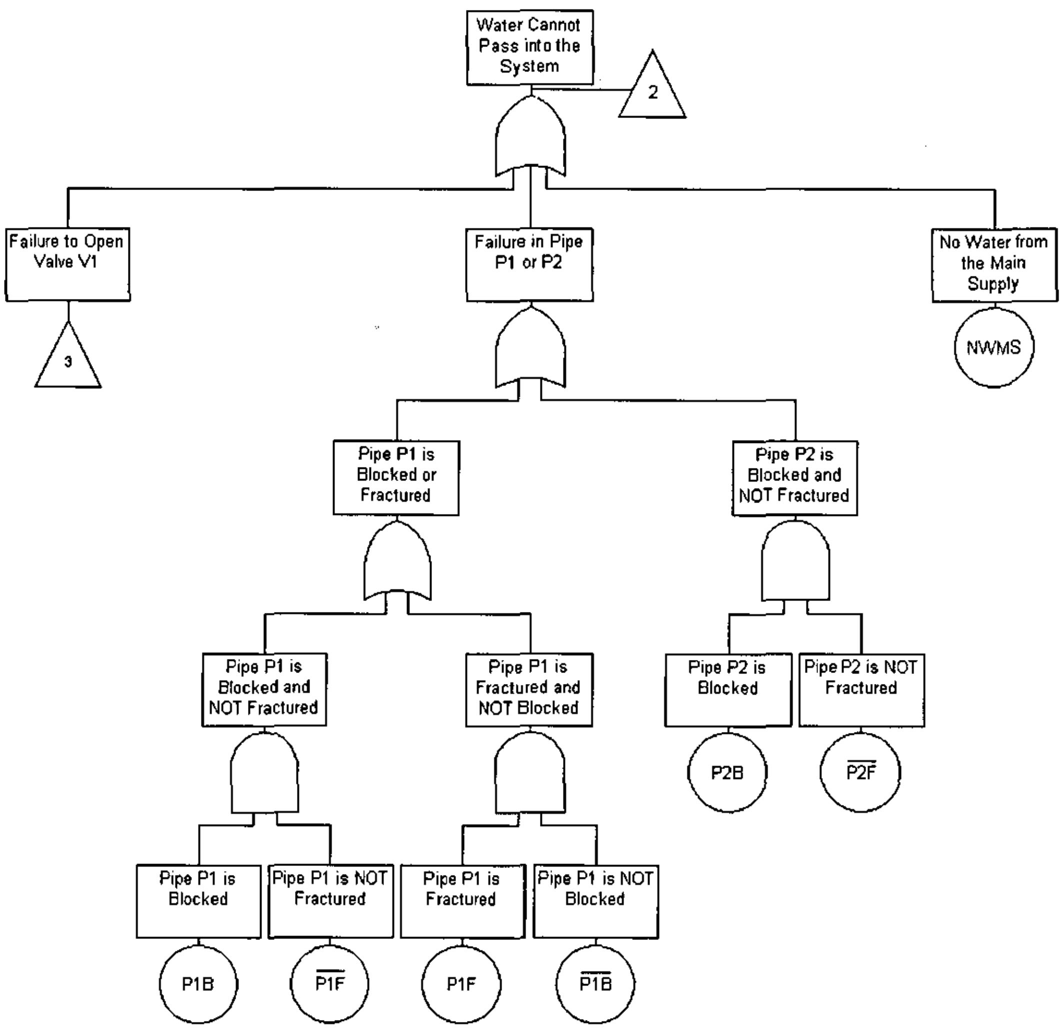


Figure 4.6: Non-Coherent fault tree for NFTV2 - transfer 2

The prime implicants for 'NFTV2' when the system is ACTIVE are listed in Table 4.5. There is 1 of single order, 9 of order 2, 1 of order 3 and 1 order 4. After performing the coherent approximation the results obtained for 'NFTV2' are the same as those obtained in Table 4.4, Section 4.3.1.1.1. When the system is in the DORMANT operating mode no flow through valve V2 is expected. In this case the prime implicant '$\overline{\text{V2FO}}$' is obtained. Performing the coherent approximation gives no potential causes of failure in this case, therefore this is omitted from the table.

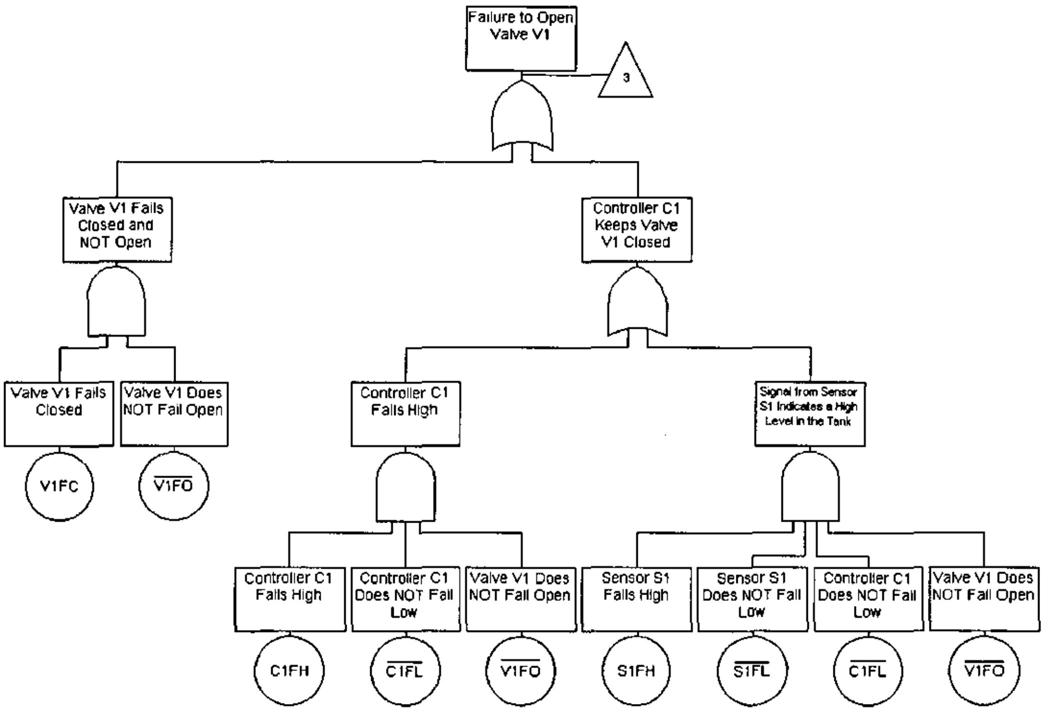


Figure 4.7: Non-Coherent fault tree for NFTV2 - transfer 3

Number	Prime Implicants
1)	NWMS
2)	P1B.$\overline{\text{P1F}}$
3)	P1F.$\overline{\text{P1B}}$
4)	P2B.$\overline{\text{P2F}}$
5)	V2FC.$\overline{\text{V2FO}}$
6)	P3B.$\overline{\text{P3F}}$
7)	P3F.$\overline{\text{P3B}}$
8)	P4B.$\overline{\text{P4F}}$
9)	TR.$\overline{\text{TL}}$
10)	V1FC.$\overline{\text{V1FO}}$
11)	C1FH.$\overline{\text{V1FO}}$.$\overline{\text{C1FL}}$
12)	S1FH.$\overline{\text{V1FO}}$.$\overline{\text{C1FL}}$.$\overline{\text{S1FL}}$

Table 4.5: Prime implicants for NFTV2
when the system is ACTIVE

4.3.2 Summary of Non-Coherent Fault Trees

Non-coherent fault trees for the other sensor readings listed in Table 4.3 are shown in Appendix A. In the same way as for 'NFTV2' the coherent fault trees are expanded to take into consideration the occurrence of component success states. In all cases after performing the coherent approximation the potential causes of failure for the non-coherent fault trees are the same as those obtained from the coherent ones.

Each non-coherent fault tree is larger than its equivalent coherent tree. For instance, for the sensor reading 'flow through valve V1' presented in Figures A.12 to A.15 to occur there must be water available into the tank. This indicates that no failure preventing flow can exist. If a component has failed in a certain way then it cannot be failed in any other or there must not be any other failure occurring that could contradict this.

4.4 System Fault Detection

Four schemes, each of differing complexity were developed to detect faults in the water tank system. The general principle was to devise a method to compare the observed and expected system behaviour and from this determine any faults that could have occurred. Fault trees were constructed from the scenarios generated using the system observation points (see Table 4.1 in Section 4.2.2.1). The four schemes have been implemented using FaultTree+ by developing the scenarios from the fault trees for the sensor readings (at the system observation points) that were originally input for verification. It has been assumed that the system was in a steady-state operating condition. In investigating the four schemes the aim is to identify the scheme with the least complexity that provides a good degree of accuracy.

4.4.1 Scheme 1

In this scheme coherent fault trees were used to develop causes of sensor deviations. At any given time the sensors must indicate one of the 16 scenarios listed in Table 4.1. If the system is ACTIVE the sensors are expected to show the readings as in scenario 4 of Table 4.1. In the DORMANT state they should show the readings in scenario 16. When the actual readings do not match the pattern of the system model it suggests a fault exists with at least one of the system components. To find all possible causes, a top event structure can be constructed from the information given by the system observation points. In this scheme only the observation points giving sensor readings that deviate from the normal operating mode of the system are considered. These are constructed by combining the causes of sensor readings (see Section 4.3.1.1), which deviate from that expected using an AND gate. This scheme is now demonstrated assuming the system is ACTIVE and the sensor readings from scenario 1 in Table 4.1 are observed.

Table 4.6 contains sensor readings expected when the system is in the ACTIVE operating mode (scenario 4) and the actual reading corresponding to scenario 1. The table shows that the sensor reading for valve V3 is 'flow', when in the ACTIVE operating mode it should be 'no flow'. Also the sensor SP1 at the observation point in the overspill tray should read 'no water' but it is indicating water is present. Hence there are two sensors that have deviated from their expected readings in the normal operating mode (highlighted in bold type).

	Scenario	V1	V2	V3	TRAY
Expected Behaviour	4 ACTIVE	F	F	NF	NW
Observed Behaviour	1	F	F	**F**	**W**

Table 4.6: ACTIVE operating mode with expected and actual sensor readings

In scheme 1 coherent fault trees for the deviated sensor readings are combined as inputs to an AND gate to form the scenario's top event structure. This is shown in Figure 4.8.

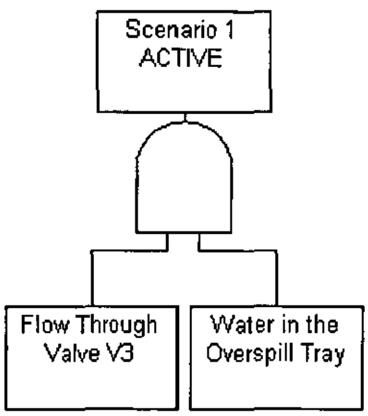


Figure 4.8: Top event structure for scenario 1 in the ACTIVE operating mode containing just deviated sensor readings

A qualitative analysis of this fault tree will produce its minimal cut sets. These are a list of all the combinations of component failures that would cause the sensor readings obtained. Analysis of the fault tree structure given in Figure 4.8 produces 102 potential causes in total; 6 of order 2 and 96 of order 3. From closer inspection though only 15 of these will result in the occurrence of the top event (3 being of order 2 and 12 of order 3). The remaining 87 are incorrect; the causes of this are now discussed. The 15 valid potential causes are listed in Table 4.7.

Number	Potential Causes	Number	Potential Causes
1)	TL.S2FH	9)	S1FL.TL.P3F
2)	TL.C2FH	10)	S1FL.TL.P4B
3)	TL.V3FO	11)	S1FL.V2FC.TL
4)	V1FO.TL.P3B	12)	C1FL.TL.P3B
5)	V1FO.TL.P3F	13)	C1FL.TL.P3F
6)	V1FO.TL.P4B	14)	C1FL.TL.P4B
7)	V1FO.V2FC.TL	15)	C1FL.V2FC.TL
8)	S1FL.TL.P3B		

Table 4.7: Potential causes of scenario 1 in the ACTIVE operating mode using scheme 1

In order for water to be present in the overspill tray there must be a leak in the tank as indicated by the results in Table 4.7, which have 'TL' in each fault combination. Flow out of the system at valve V3 can occur either due to a failure at the valve or because the level of water has got too high in the system and it has opened to reduce this.

In considering why the analysis has produced incorrect results, the coherent fault trees for the sensor readings 'flow through valve V3' and 'water in the overspill tray' are both valid when analysed individually. However, one of the reasons for obtaining 'water in the overspill tray' is that no flow through valve V3 occurs, contradicting the sensor reading 'flow through valve V3'. Without NOT logic present in the fault trees to indicate the component working states conflicting potential causes are not removed. For example, one of the incorrect minimal cut sets is V1FO.P3B.P5B. This minimal cut set would give water in the overspill tray, however pipe P5 is blocked so water cannot get through V3, contradicting the top event structure. Therefore, coherent fault trees representing sensor deviations do not contain enough information about system behaviour, with the resulting implication that scheme 1 is not a very accurate method.

In addition to the problem of invalid potential causes the number of valid possibilities listed in Table 4.7 for scenario 1 is quite large. This has also been the case for a number of the other scenarios. A method is required to reduce this number of potential causes to as few as possible. Scheme 1 does not take into account the sensor readings from the observation points in the scenario that are correct for the chosen operating mode. Only the first 3 potential causes actually produce scenario 1 when the sensor readings from the observation points at valves V1 and V2 are taken into account. The other potential causes are all valid for the sensor reading flow through V1, but would result in no flow through valve V2. This issue is addressed in scheme 2 to try and improve the diagnostic capability. Information from the sensors that are operating correctly is used to evaluate which parts of the system must be functioning with the deviated sections, hence discounting them from the list of potential failures.

4.4.2 Scheme 2

Coherent fault trees for sensor readings are also used in scheme 2. In this case though a consistency check is introduced into the model by including information from all sensor readings obtained from the analysis in the construction of the top event for the observed system state. Expected readings from sensors are included as NOT failed events in the top event structure. (For example, if the sensor reading for valve V1 were 'flow' then this would be equivalent to saying that there is 'NOT no flow'. This therefore produces a list of working states for flow through valve V1). Writing them in their equivalent negated form now includes sensor readings not considered in scheme 1 that are true to the chosen operating mode. Hence the strategy for scheme 2 is for the fault trees for a given set of sensor readings to be combined including both deviations and those expected in their equivalent negated form using an AND gate. Scheme 2 is now demonstrated using the observed sensor readings of scenario 1.

Table 4.8 below contains the ACTIVE operating mode for the system (scenario 4) and scenario 1 with the sensor readings for valves V1 and V2 written in negated form (the bar over the deviated sensor reading means 'NOT that deviated sensor reading').

	Scenario	V1	V2	V3	TRAY
Expected Behaviour	4 ACTIVE	F	F	NF	NW
Observed Behaviour	1	$\overline{\textbf{NF}}$	$\overline{\textbf{NF}}$	**F**	**W**

Table 4.8: ACTIVE operating mode and scenario 1

Fault trees for these negated sensor readings can now be obtained and included in the model along with those for the deviated sensor readings in order to check consistency. The trees are combined with an AND gate, as shown in Figure 4.9.

The cause of NOT no flow through valve V1 is:

$$\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{S1FH}.\overline{C1FH}.\overline{V1FC}.\overline{NWMS}.\overline{P3B}.\overline{P4B}.\overline{V2FC}$$

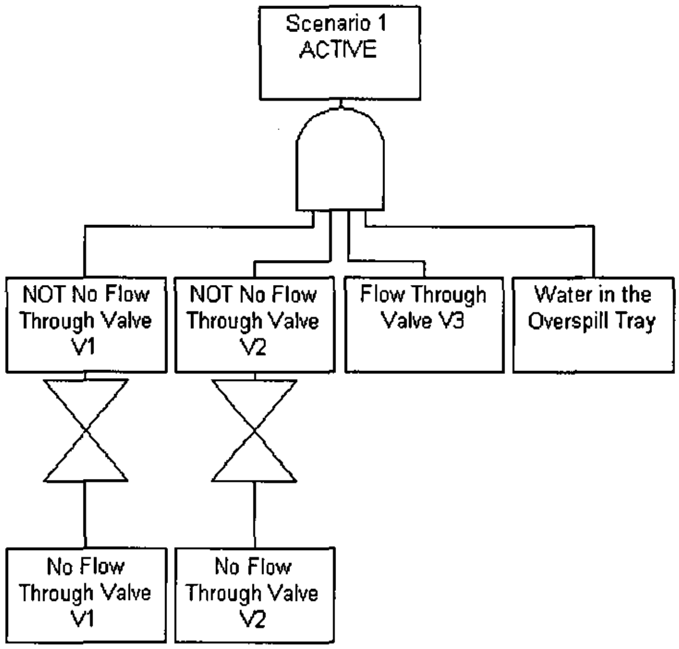


Figure 4.9: Top event structure for scenario 1 in the ACTIVE operating mode containing both deviated sensor readings and consistency checks

The cause of NOT no flow through valve V2 is:

$$\overline{TR}.\overline{NWMS}.\overline{P3B}.\overline{P3F}.\overline{P4B}.\overline{V2FC}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{S1FH}.\overline{C1FH}.\overline{V1FC}$$

These combined (ANDed) together with the potential causes listed in Table 4.7 from scheme 1 shows that scheme 2 produces 3 prime implicants representing the potential causes of scenario 1 in the ACTIVE operating mode; these are listed in Table 4.9. These potential causes include the working components. Removing these produces a list of the potential causes containing only failed components, as shown in the 'Coherent Approximation' column.

These are all valid potential causes of scenario 1. This shows that for this particular scenario scheme 2 is a better model at pinpointing the actual cause compared to scheme 1, reducing the correct number of potential causes from 15 to 3 with the inclusion of working sensors. However, scheme 1 showed that coherent fault trees do not contain enough information about system behaviour to obtain a reliable list of potential causes. Scheme 2 uses the same fault trees, so invalid results from combining the deviated sensor readings can still occur, for example in the situation where all sensors in the system are deviated. This problem can be alleviated by using non-coherent fault trees that contain NOT logic. These trees are introduced into the analysis for each sensor reading in scheme 3 in order to indicate which components are working.

Number	Potential Causes	Coherent Approximation
1)	$\overline{NWMS}.\overline{TR}.\overline{P2B}.\overline{P1F}.\overline{P1B}.\overline{V2FC}.TL.\overline{P4B}.\overline{P3B}.\overline{P3F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.S2FH$	TL.S2FH
2)	$\overline{NWMS}.\overline{TR}.\overline{P2B}.\overline{P1F}.\overline{P1B}.\overline{V2FC}.TL.\overline{P4B}.\overline{P3B}.\overline{P3F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.C2FH$	TL.C2FH
3)	$\overline{NWMS}.\overline{TR}.\overline{P2B}.\overline{P1F}.\overline{P1B}.\overline{V2FC}.TL.\overline{P4B}.\overline{P3B}.\overline{P3F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.V3FO$	TL.V3FO

Table 4.9: Potential causes of scenario 1 in the ACTIVE operating mode using scheme 2

4.4.3 Scheme 3

In scheme 3 system behaviour is modelled using non-coherent fault trees. As in scheme 1 the observed system sensor readings are obtained from the observable points. A fault tree structure is constructed using only the sensor readings that have deviated from the normal system operating mode. Therefore it does not include a consistency check. To illustrate scheme 3 the top event structure (assuming, as before, the sensor readings represented by scenario 1 have been obtained), can be constructed in the same way as for scheme 1 (see Figure 4.8), but using non-coherent fault trees for the deviated sensor readings 'flow through valve V3' and 'water in the overspill tray'.

Analysis of the faults, as in scheme 2, produces prime implicants. 15 potential causes of scenario 1 are produced by scheme 3. After removing the working state events these are the same as those obtained by scheme 1 that are valid for the deviated sensor readings (see Table 4.7). Scheme 3 therefore shows that introducing NOT logic into the fault trees indicates which components are working for each deviated sensor reading and removes any conflicting potential causes (namely the previous 87 incorrect causes obtained in scheme 1).

There are again quite a large number of alternatives and it would be difficult to determine which one could be the actual cause. This is also the case for some of the results for other scenarios. In the same way as for scheme 1, scheme 3 does not take into account the sensor readings from the observation points in the scenario that are correct for the chosen operating mode. Some of the potential causes listed in the example may be invalid given the functionality of the other areas of the system. This scheme has failed to differentiate between the potential causes and so scheme 4, which contains the additional complexity of non-coherent sensor deviations with consistency checks, may provide a better analysis option.

4.4.4 Scheme 4

Scheme 4 models system behaviour using non-coherent fault trees for sensor deviations. The top event structure for scenario 1 using scheme 4 is shown in Figure 4.8. Analysis of the faults, as in schemes 2 and 3 produces prime implicants. Removing the working component states gives the coherent approximation. There are 3 potential causes of scenario 1, listed in Table 4.10.

Number	Potential Causes
1)	TL.S2FH
2)	TL.C2FH
3)	TL.V3FO

Table 4.10: Potential causes of scenario 1 in the ACTIVE operating mode using scheme 4

The potential causes of scenario 1 in Table 4.10 are the same as those obtained using scheme 2 after removing the working components (see Table 4.9). This shows that schemes 2 and 4 are better models than 1 and 3 at pinpointing the actual cause of scenario 1. Compared to the result obtained from scheme 3 the model in scheme 4 strengthens the belief that not enough information is being obtained by only considering sensors that have deviated from their expected readings.

4.5 Discussion of the System Fault Detection Method

4.5.1 Introduction

Four fault tree based schemes for detecting faults or combinations of faults in systems have been introduced. Each scheme was demonstrated using the water tank level control system example. Each of the scenarios listed in Table 4.1 were constructed in FaultTree+ for the four schemes in the ACTIVE and DORMANT operating modes. The top events for each of the scenarios were constructed by hand using the given expected behaviour from each mode to determine the fault trees required for each of the sensor readings. This enabled the construction of single and multiple symptom top events depending on the chosen scenario. The automation of the fault trees for each of the sensor readings enabled analysis for each of the possible scenarios for the four schemes and their given operating modes to be carried out more quickly than could be done by hand. Once results were obtained the potential causes of failure were verified by hand and compared with those expected for each scenario. Expected potential causes of failure for each scenario were identified by comparing what was happening in the system with that expected by visual inspection. This enabled the results obtained from FaultTree+ to be verified. The performance of the four schemes has been investigated to evaluate their potential to identify the causes of all 16 scenarios, both in the ACTIVE and DORMANT operating modes. The results for each of the schemes are now discussed.

4.5.2 Tank System Results

Schemes 1 to 4 were applied to produce the causes of the 16 scenarios of possible sensor readings listed in Table 4.1. An index to indicate the scheme effectiveness is calculated.

4.5.2.1 Effectiveness Index for the Schemes

An index has been applied to each of the schemes to give some indication of their relative merit. For each scheme the number of possible causes of each scenario is recorded, along with a list of causes obtained and how many of the correct causes are included in this list. The index is used on each scheme to indicate how effective it has been at obtaining correct potential causes of failure over the 15 scenarios for each of the operating modes (ACTIVE/DORMANT) that contain at least one deviated sensor reading (one of the scenarios represents the symptoms of a fully functioning system).

4.5.2.1.1 Definition of Effectiveness Index

The Effectiveness Index $I_{E_{jk}}$ used is defined as:

$$I_{E_{jk}} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{nc_i}{n_i}\right).\left(\frac{nc_i}{na_i}\right)$$

where,

N = The number of scenarios investigated.

n_i = The number of potential causes of failure *identified* by the scheme for scenario i. (These were obtained using FaultTree+).

nc_i = The number of *correct* potential causes of failure obtained by the scheme for scenario i. (These identified by visual inspection).

na_i = The number of *actual* potential causes of failure that should have been obtained by the method for scenario i. (These were identified by hand).

j = The scheme number.

k = ACTIVE and DORMANT operating modes (represented by an 'A' and 'D' respectively).

The index has a range from 0 to 1, with 0 indicating a scheme that is not effective and 1 the most effective possible. Note that in the ideal situation the fault detection system will identify only one cause of each scenario and it will be correct, producing an effectiveness index of 1. Indices not equal to 1 are expected in practice because there will never be enough sensors to provide sufficient information to diagnose each fault. The index is used because it is easy and fast to calculate and is indicative of the benefit of each scheme.

4.5.2.2 Results for Scheme 1

Results obtained for scheme 1 in the ACTIVE and DORMANT operating modes are shown in Table 4.11. The table contains, for each scenario, the number of possible causes produced by the scheme, n_i, and the number of these that are correct causes of the symptoms observed, nc_i for the respective mode. The actual number of causes, na_i, that would have been produced if the scheme gave a perfectly correct list is also indicated in the final column of each mode section of the table (this takes into account the functionality of the whole system). The actual possibilities have been calculated by hand.

The results for scheme 1 show that in many cases entries in the list of potential causes obtained for the scenarios did not cause the symptoms shown. For example, this has occurred in scenario 1 in the ACTIVE operating mode, where the number of possible causes produced by the scheme is 102, but the number valid for the deviated readings is 15. The number actually correct - if considering the readings that are true to the operating mode - is only 3. Scenarios 5, 6, 9, 10, 13, 14 and 15 in the ACTIVE operating mode and in 1, 5, 9 and 13 in the DORMANT mode (Table 4.11) also contain failures that are not valid for the given deviated readings. Fifteen of the results as shown in Section 4.4.1 for scenario 1 will produce the deviated sensor readings 'flow through valve V3' and 'water in the overspill tray'. However, taking into consideration all readings including those expected for the operating mode 12 of these readings that are valid for the deviated sensor readings are invalid when considering the readings true to the operating mode. This example, along with other results shown in Table 4.11 indicates that a check of some form is required in order to consider readings of the non-deviated sensors.

					ACTIVE			DORMANT		
Scenario	V1	V2	V3	TRAY	Results from Scheme 1		Number of Actual Possibilities	Results from Scheme 1		Number of Actual Possibilities
					n_i	nc_i	na_i	n_i	nc_i	na_i
1	F	F	F	W	102	3	3	30	3	3
2	F	F	F	NW	15	3	3	6	3	3
3	F	F	NF	W	74	1	1	20	1	1
4	F	F	NF	NW	-	-	-	1	1	1
5	F	NF	F	W	132	24	24	30	6	6
6	F	NF	F	NW	48	24	24	6	6	6
7	F	NF	NF	W	84	77	77	20	20	20
8	F	NF	NF	NW	12	4	4	11	5	5
9	NF	F	F	W	300	21	21	30	3	3
10	NF	F	F	NW	60	21	21	6	3	3
11	NF	F	NF	W	200	7	7	20	1	1
12	NF	F	NF	NW	10	7	7	1	1	1
13	NF	NF	F	W	300	0	84	30	3	3
14	NF	NF	F	NW	60	0	84	6	3	3
15	NF	NF	NF	W	200	14	14	20	2	2
16	NF	NF	NF	NW	10	10	10	-	-	-
		Effectiveness Index			$I_{E_{1A}} = 0.293$			$I_{E_{1D}} = 0.444$		

Table 4.11: Results obtained for scheme 1 in the ACTIVE and DORMANT operating modes

The fault trees used in this scheme are coherent, and when analysed individually they are valid. The trees are combined to give the causes of unexpected readings and they may contain conflicting potential causes of failure. Without the use of NOT logic in the fault trees these conflicts will still exist in the results, and therefore cannot be eliminated from the list of possibilities.

The validity of some results were found to be dependent upon the amount of water in the tank, which strengthened the need for the consideration of transient effects. For instance the results for scenario 16 are: {{P1B}, {P1F}, {P2B}, {V1FC}, {C1FH}, {S1FH}, {NWMS}, {P3B}, {P4B}, {V2FC}}. The first 7 potential causes are valid if there is no longer any water in the tank and the remaining 3 are valid if no water has left the tank and the level is at that required. This shows that transient effects within the system must be considered in order to develop the fault diagnostic method further.

The results have shown that there is not enough information about the system behaviour in coherent fault trees to yield an accurate list of potential causes, therefore scheme 1 is not a very good fault diagnostic method. This is reflected in the Effectiveness Index, which was calculated as $I_{E_{1A}} = 0.293$ for the ACTIVE mode and $I_{E_{1D}} = 0.444$ for the DORMANT mode, giving an average of $I_{E_1} = 0.368$.

As well as the problem of invalid potential causes of failure scheme 1 does not take into consideration the sensors that are indicating the expected value for the operating mode. Correct potential causes obtained by considering only the deviated sensor readings may be valid for those readings, but it is not valid when considering the overall system and the additional information provided by the sensors with expected readings. The ability to consider all information would reduce the number of potential causes of failure and therefore give a more accurate list of possibilities. The sensors reading as expected for the operating mode are introduced into the analysis in scheme 2.

4.5.2.3 Results for Scheme 2

Table 4.12 lists the potential causes of failure for scheme 2 in the ACTIVE and DORMANT operating modes, after removing the working components (the Coherent Approximation).

					ACTIVE					DORMANT				
Scenario	V1	V2	V3	TRAY	Results from Scheme 2 (I)		Results from Scheme 2 (II)		Number of Actual Possibilities	Results from Scheme 2 (I)		Results from Scheme 2 (II)		Number of Actual Possibilities
					n_i	nc_i	n_i	nc_i	na_i	n_i	nc_i	n_i	nc_i	na_i
1	F	F	F	W	3	3	3	3	3	30	3	30	3	3
2	F	F	F	NW	3	3	3	3	3	6	3	6	3	3
3	F	F	NF	W	1	1	1	1	1	20	1	20	1	1
4	F	F	NF	NW	-	-	-	-	-	1	1	1	1	1
5	F	NF	F	W	30	3	111	24	24	30	6	30	6	6
6	F	NF	F	NW	6	6	24	24	24	6	6	6	6	6
7	F	NF	NF	W	20	20	77	77	77	20	20	20	20	20
8	F	NF	NF	NW	1	1	4	4	4	5	5	5	5	5
9	NF	F	F	W	0	0	21	21	21	0	0	6	3	3
10	NF	F	F	NW	0	0	21	21	21	0	0	3	3	3
11	NF	F	NF	W	0	0	7	7	7	0	0	2	1	1
12	NF	F	NF	NW	0	0	7	7	7	0	0	1	1	1
13	NF	NF	F	W	300	0	300	0	84	0	0	6	3	3
14	NF	NF	F	NW	60	0	60	0	84	0	0	3	3	3
15	NF	NF	NF	W	200	14	200	14	14	0	0	2	2	2
16	NF	NF	NF	NW	10	10	10	10	10	-	-	-	-	-
				Effectiveness Index	$I_{E_{2(I)A}} = 0.323$ and $I_{E_{2(II)A}} = 0.752$					$I_{E_{2(I)D}} = 0.323$ and $I_{E_{2(II)D}} = 0.690$				

Table 4.12: Results obtained for scheme 2 in the ACTIVE and DORMANT operating modes

Two ways of performing consistency checks were investigated in the analysis and shown in the Table. The first, labelled 'scheme 2(I)', includes the sensor readings that are expected for the operating mode in their negated form in the top event structure. These checks may include symptoms that change in time, for example, 'flow through valve V3' may be caused by V3 failing open, controller C2 failing high or sensor S2 reading a high level of water in the tank. This may also be the result of uncontrollable flow into the system through V1 and no flow out at V2. This latter situation does not cause the effect immediately. Initially it results in an increasing water level and as a result the safety valve opening. The second consistency check is labelled 'scheme 2(II)', and in this case only the immediate causes of the effects predicted by the sensors reading true to the operating mode are included in the fault trees. Therefore working states where the symptoms change in time are not taken into consideration.

'Scheme 2(I)' shows that the results for the ACTIVE operating mode have not improved compared to those obtained by scheme 1, and this is reflected in the effectiveness index result. Results for scenarios 1, 2 and 3 in the ACTIVE operating mode (in the ACTIVE column in Table 4.12) have all improved compared to those from scheme 1. There are however a number of scenarios that have either resulted in the method obtaining no potential causes of failure or no valid ones, for example scenarios 9 to 14 in the ACTIVE operating mode. This has also occurred in the results for the DORMANT operating mode in scenarios 9 to 15 (Table 4.12). The majority of these scenarios have flow out of the system but no flow in. For example, if the sensor readings indicate that the system is in scenario 9 in the ACTIVE operating mode, then the deviated sensor readings are 'no flow through valve V1', 'flow through valve V3' and 'water in the overspill tray'. In scheme 1 these deviated sensor readings gave a list of 300 possible potential causes of failure (see Table 4.11).

The extra information for the flow sensor at V2 'Flow through valve V2' is equivalent to saying there is 'NOT no flow through valve V2', which produces a list of working states causing the expected flow through V2. However, 'no flow through valve V2' could be caused by the tank being empty as a result of no water coming into the system through valve V1. The point at which there is no flow through valve V2 would be dependent on the amount of water originally in the tank, and the rate at which it is decreasing. The flow through V2 symptom therefore changes in time. Flow out at V2 and V3 indicates that there must be water in the tank, else the system would not be in scenario 9. This is in conflict with the sensor indicating 'no flow through valve V1', leaving no potential causes of failure when there should be 21 possibilities.

'Scheme 2(II)' uses a consistency check that only takes into consideration the symptoms that would cause an immediate effect on the system when checked against the deviated sensor readings. For example, in scenario 9 in the ACTIVE operating mode 'no flow through valve V2' would immediately occur if V2 suddenly failed closed, pipe P3 became blocked or fractured, P4 became blocked, or the tank ruptured. No flow into the system through V1 may take time to cause no flow through V2, therefore it is not checked against the three deviated sensor readings. This gives 21 potential causes of failure for the scenario.

The effectiveness index of $I_{E_{2(\mathrm{II})\mathrm{A}}} = 0.752$ for the ACTIVE mode and $I_{E_{2(\mathrm{II})\mathrm{D}}} = 0.690$ for the DORMANT mode in scheme 2(II), giving an average of $I_{E_{2(II)}} = 0.721$ shows that there is an improvement in comparison to the indices produced by scheme 1. However, scheme 1 illustrated that coherent fault trees do not contain enough information about the system behaviour to obtain reliable results. Scheme 2 also uses coherent fault trees and invalid results have still occurred in (II), for example in the DORMANT operating mode in scenario 1 (which contains all deviated sensor readings, so is equivalent to scenario 1 in scheme 1), 5, 9 and 13. As concluded in scheme 1, without the use of NOT logic in the actual fault trees conflicts may still occur between causes of the sensor readings.

4.5.2.4 Results for Scheme 3

The use of NOT logic is introduced into the fault trees in this scheme. Therefore when the deviated sensor readings are considered together, any conflicting potential causes of failure should be removed from the list of possible causes. Results obtained for scheme 3 in the ACTIVE and DORMANT operating modes are shown in Table 4.13. The top event structure only contains deviated sensor readings, as in scheme 1.

The results obtained for both the ACTIVE and DORMANT operating modes have shown that the use of NOT logic in the fault trees has removed all of the the invalid potential causes of failure that were present in some scenarios for both schemes 1 and 2 when combining just the deviated sensor readings. As a result, in the majority of cases, the number of potential causes of failure obtained is less than compared to those in scheme 1.

The effectiveness index value is $I_{E_{3\mathrm{A}}} = 0.459$ and $I_{E_{3\mathrm{D}}} = 0.837$ for the ACTIVE and DORMANT modes respectively, with an average of $I_{E_3} = 0.648$. This is an improvement on scheme 1, which had an average of 0.368, but not to that for scheme 2 (II), which was $I_{E_{2(II)}} = 0.721$. As is consistent with scheme 1, not taking account of the readings from the sensors giving expected readings for the operating mode has resulted in an inaccurate list of potential causes for some scenarios, for example in scenarios 1 to 8 in the ACTIVE operating mode (see Table 4.13). The sensors reading expected values for the operating mode are introduced in scheme 4.

					ACTIVE			DORMANT		
Scenario	V1	V2	V3	TRAY	Results from Scheme 3		Number of Actual Possibilities	Results from Scheme 3		Number of Actual Possibilities
					n_i	nc_i	na_i	n_i	nc_i	na_i
1	F	F	F	W	15	3	3	3	3	3
2	F	F	F	NW	15	3	3	3	3	3
3	F	F	NF	W	74	1	1	1	1	1
4	F	F	NF	NW	-	-	-	1	1	1
5	F	NF	F	W	45	24	24	6	6	6
6	F	NF	F	NW	45	24	24	6	6	6
7	F	NF	NF	W	84	77	77	20	20	20
8	F	NF	NF	NW	12	4	4	11	5	5
9	NF	F	F	W	30	21	21	3	3	3
10	NF	F	F	NW	30	21	21	3	3	3
11	NF	F	NF	W	20	7	7	1	1	1
12	NF	F	NF	NW	10	7	7	1	1	1
13	NF	NF	F	W	30	0	84	6	3	3
14	NF	NF	F	NW	30	0	84	6	3	3
15	NF	NF	NF	W	20	14	14	20	2	2
16	NF	NF	NF	NW	10	10	10	-	-	-
		Effectiveness Index			$I_{E_{3A}} = 0.459$			$I_{E_{3D}} = 0.837$		

Table 4.13: Results obtained for scheme 3 in the ACTIVE and DORMANT operating modes

4.5.2.5 Results for Scheme 4

Table 4.14 lists the potential causes of failure for each scenario as established by scheme 4 in the ACTIVE and DORMANT operating modes, after removing the working components. As in the third scheme, the fourth scheme also uses non-coherent fault trees in the system analysis. A consistency check was introduced as in scheme 2 to allow the sensors reading true to the operating mode to be included. As in scheme 2, two checks were investigated.

Investigations using negated non-coherent fault trees to include the information provided by those sensors that have the expected readings in the top event structures gave some inaccurate results. This was because some 'NOT' events in the fault trees were becoming potential causes of failure as a result of being negated twice. Using non-coherent fault trees in the consistency check (scheme 4 (I)) gave no additional input into the analysis, but increased the complexity. Therefore a consistency check was carried out by taking the results obtained when considering just the deviated sensor readings and checking them individually against the sensors reading true to the operating mode. Any results that lead to a contradiction were then removed from the list. These results are shown in Table 4.14 under the column heading 'Scheme 4 (II)' for ACTIVE and DORMANT operating modes.

					ACTIVE					DORMANT				
Scenario	V1	V2	V3	TRAY	Results from Scheme 4 (I)		Results from Scheme 4 (II)		Number of Actual Possibilities	Results from Scheme 4 (I)		Results from Scheme 4 (II)		Number of Actual Possibilities
					n_i	nc_i	n_i	nc_i	na_i	n_i	nc_i	n_i	nc_i	na_i
1	F	F	F	W	3	3	3	3	3	3	3	3	3	3
2	F	F	F	NW	3	3	3	3	3	3	3	3	3	3
3	F	F	NF	W	1	1	1	1	1	1	1	1	1	1
4	F	F	NF	NW	-	-	-	-	-	1	1	1	1	1
5	F	NF	F	W	15	15	24	24	24	6	6	6	6	6
6	F	NF	F	NW	15	15	24	24	24	6	6	6	6	6
7	F	NF	NF	W	107	73	77	77	77	20	20	20	20	20
8	F	NF	NF	NW	88	1	4	4	4	29	2	5	5	5
9	NF	F	F	W	0	0	21	21	21	0	0	3	3	3
10	NF	F	F	NW	0	0	21	21	21	0	0	3	3	3
11	NF	F	NF	W	0	0	7	7	7	0	0	1	1	1
12	NF	F	NF	NW	0	0	7	7	7	0	0	1	1	1
13	NF	NF	F	W	30	0	30	0	84	21	0	3	3	3
14	NF	NF	F	NW	30	0	30	0	84	23	0	3	3	3
15	NF	NF	NF	W	14	14	20	14	20	14	0	2	2	2
16	NF	NF	NF	NW	10	10	10	10	10	-	-	-	-	-
		Effectiveness Index			$I_{E_{4(I)A}} = 0.460$ and $I_{E_{4(II)A}} = 0.847$					$I_{E_{4(I)D}} = 0.469$ and $I_{E_{4(II)D}} = 1.000$				

Table 4.14: Results obtained for scheme 4 in the ACTIVE and DORMANT operating modes

Results in the ACTIVE operating mode from scheme 4(I) - which takes into consideration all possible symptoms - gave an index of $I_{E_{4(I)A}} = 0.460$. This shows that there is an improvement in scheme 4 compared to results for schemes 1 and 2(I), as indicated in the effectiveness index values, which are $I_{E_{1A}} = 0.293$, $I_{E_{2(I)A}} = 0.323$, but the result was not as good as that for scheme 3, which was $I_{E_{3A}} = 0.459$. As in scheme 2(I) where there are a number of scenarios that have either resulted in the method obtaining no potential causes of failure or no valid ones, this has also occurred in the DORMANT mode. Again this was found to be because the check being carried out checked the list of potential causes against all symptoms true to the operating mode.

As in scheme 2(II), scheme 4(II) checks for consistency using only failures that would have an immediate affect on the system. The effectiveness index in this case was $I_{E_{4(II)A}} = 0.847$ for the ACTIVE and $I_{E_{4(II)D}} = 1.000$ for the DORMANT operating modes, giving an average of $I_{E_{4(II)}} = 0.924$. This average is an improvement compared to all of the other three schemes.

Therefore, the usage of non-coherent fault trees and a consistency check that considers failures that immediately affect the system as shown in scheme 4 (II), is the most accurate of the schemes 1 to 4 for modelling behaviour of the water tank system.

4.5.3 Discussion

4.5.3.1 Overview of Results

A summary of the results obtained for schemes 1 to 4 applied to the simple tank system operating in the ACTIVE and DORMANT modes, and their respective effectiveness indices are shown in Tables 4.15 and 4.16.

The performance of the four schemes has been investigated to evaluate their potential to identify the causes of all 16 scenarios, both in ACTIVE and DORMANT operating modes for the system. Schemes 1 and 2 have produced potential causes that are invalid to the top event structure, both for scenario 1 and a number of others. This is the case even though the fault trees for each of the sensor readings are correct when analysed individually. For example, for scenario 5 in the ACTIVE operating mode schemes 1 and 2 produce 132 and 111 potential causes respectively for their top event structures. Only 24 of these results for the two schemes are actually valid even though the fault trees for the sensor readings are correct when analysed individually. For certain scenarios scheme 2 has also removed potential causes that are valid for the top event structure. This implies that there is not enough information in the coherent fault trees to explain the system behaviour.

Scenario	V1	V2	V3	TRAY	Scheme 1		Scheme 2		Scheme 3		Scheme 4		Number of Actual Possibilities
					n_i	nc_i	n_i	nc_i	n_i	nc_i	n_i	nc_i	na_i
1	F	F	F	W	102	3	3	3	15	3	3	3	3
2	F	F	F	NW	15	3	3	3	15	3	3	3	3
3	F	F	NF	W	74	1	1	1	74	1	1	1	1
4	F	F	NF	NW	-	-	-	-	-	-	-	-	-
5	F	NF	F	W	132	24	111	24	45	24	24	24	24
6	F	NF	F	NW	48	24	24	24	45	24	24	24	24
7	F	NF	NF	W	84	77	77	77	84	77	77	77	77
8	F	NF	NF	NW	12	4	4	4	12	4	4	4	4
9	NF	F	F	W	300	21	21	21	30	21	21	21	21
10	NF	F	F	NW	60	21	21	21	30	21	21	21	21
11	NF	F	NF	W	200	7	7	7	20	7	7	7	7
12	NF	F	NF	NW	10	7	7	7	10	7	7	7	7
13	NF	NF	F	W	300	0	300	0	30	0	30	0	84
14	NF	NF	F	NW	60	0	60	0	30	0	30	0	84
15	NF	NF	NF	W	200	14	200	14	20	14	20	14	14
16	**NF**	**NF**	**NF**	**NW**	10	10	10	10	10	10	10	10	10
Effectiveness Index I_{E_j}					0.293		0.752		0.459		0.837		

Table 4.15: Results obtained for schemes 1 to 4 in the ACTIVE operating mode and effectiveness index

Non-coherent fault trees were introduced into schemes 3 and 4. These have eliminated any invalid potential causes of failure from combining the deviated sensor readings. Scheme 3 still does not consider readings that are true to the operating mode. Scheme 4, which includes all sensor readings, is the best scheme for modelling the system.

For each scheme and each scenario the table contains the number of possible causes produced by the scheme, n_i, and the number of these that are correct causes of the symptoms observed, nc_i. The actual number of causes, na_i, that would have been produced if the scheme gave a perfectly correct list is indicated in the final column of the table.

When the working states are considered as in scheme 2 the effectiveness is improved as indicated by the average index for ACTIVE and DORMANT system operating states increasing from 0.368 in Scheme 1 ($I_{E_{1A}} = 0.293 + I_{E_{1D}} = 0.444$ divided by 2 to give the average $I_{E_1} = 0.368$) to 0.721 in Scheme 2 ($I_{E_{2(II)A}} = 0.752 + I_{E_{2(II)D}} = 0.690$ divided by 2 to give the average $I_{E_{2(II)}} = 0.721$). Even with this improvement overall the results imply that coherent fault trees do not contain enough information about the system behaviour to produce an accurate list of potential causes.

Scenario	V1	V2	V3	TRAY	Scheme 1		Scheme 2		Scheme 3		Scheme 4		Number of
					n_i	nc_i	n_i	nc_i	n_i	nc_i	n_i	nc_i	Actual Possibilities
1	F	F	F	W	30	3	30	3	3	3	3	3	3
2	F	F	F	NW	6	3	6	3	3	3	3	3	3
3	F	F	NF	W	20	1	20	1	1	1	1	1	1
4	F	F	NF	NW	1	1	1	1	1	1	1	1	1
5	F	NF	F	W	30	6	30	6	6	6	6	6	6
6	F	NF	F	NW	6	6	6	6	6	6	6	6	6
7	F	NF	NF	W	20	20	20	20	20	20	20	20	20
8	F	NF	NF	NW	11	5	5	5	11	5	5	5	5
9	NF	F	F	W	30	3	6	3	3	3	3	3	3
10	NF	F	F	NW	6	3	3	3	3	3	3	3	3
11	NF	F	NF	W	20	1	2	1	1	1	1	1	1
12	NF	F	NF	NW	1	1	1	1	1	1	1	1	1
13	NF	NF	F	W	30	3	6	3	6	3	3	3	3
14	NF	NF	F	NW	6	3	3	3	6	3	3	3	3
15	NF	NF	NF	W	20	2	2	2	20	2	2	2	2
16	NF	NF	NF	NW	-	-	-	-	-	-	-	-	-
Effectiveness Index I_{E_j}					0.444		0.690		0.837		1.000		

Table 4.16: Results obtained for schemes 1 to 4 in the DORMANT operating mode and effectiveness index

The use of NOT logic to indicate the working component states is introduced into the fault trees in scheme 3. This has eliminated all of the invalid potential causes of failure that were produced by combining the fault trees for the deviated sensor readings. The results show an improvement compared to scheme 1, but not to scheme 2. This is because scheme 3 does not take into consideration the sensors reading true to the operating mode. The fourth scheme uses non-coherent fault trees to develop causes of both deviated sensor readings and sensors reading expected values and combine these to form the top event structure. The causes obtained in this way are more accurate than those obtained by the other schemes.

Two consistency checks were used in schemes 2 and 4. Results have shown that only taking into consideration the symptoms that would cause an immediate affect on the system is the better of the two checks. This is an indication of a limitation of the approach developed in that it is not capable of dealing with situations where the symptoms change in time. The introduction of a consistency check in schemes 2 and 4 has resulted in a net improvement compared to schemes 1 and 3 respectively. The effectiveness index values together with the information obtained from the analysis in schemes 1 to 3 has shown that scheme 4 is the best model for obtaining potential causes of the 16 scenarios in ACTIVE and DORMANT modes for the water tank system in steady state.

4.5.3.2 Scalability and Consistency Checks

The four methods presented for diagnosing faults in systems use FTA to explain the deviations from normal values observed in the sensed variables. The effectiveness of the methods has been investigated using a simple example containing only a small number of components. Application to a larger system is required in order to show how effective the methods would be when used on real systems.

The computational expense of processing a large number of sensors would not enable the schemes considered so far to be applied directly to a real system. Even when only checking immediate symptoms the NOT logic used in scheme 4 would be computationally intensive. The consistency check used in this scheme involves taking the potential causes obtained from only the deviated sensor readings and checking these individually against the causes of sensors reading true to the operating mode. Any potential causes of the deviated sensor readings that lead to a contradiction in the expected sensor readings can then be removed from the list.

The consistency check aspect would be fine for larger systems. The qualitative analysis of a top event constructed of the non-coherent fault trees for causes of the deviated sensors would, however, be a problem. A means of resolving the issue needs to be found in the future work.

4.5.3.3 Imperfect Sensors

The method illustrated in this chapter has been applied to an example that does not account for the possibility of sensor failures in the system. One method to accommodate these sensor failures is to incorporate failed sensor events into the fault trees for each sensor reading and the analysis performed in the same way. Another approach could be to try to establish the validity of sensor readings at the start of the analysis and only consider data on system symptoms that is known to be reliable. For the simple tank system the validity of the flow sensor readings could be established by considering information provided by the level sensors S1 and S2. A comparison can be made of these together with the tank level calculated from the volume flow rate and spill tray sensors, VF1, VF2, VF3 and SP1, in order to identify any defective readings.

4.5.3.4 Obtaining the Exact Cause of Failure

Ideally the fault detection scheme would be perfect and would determine the exact cause of each scenario. However, in reality this would require a great deal of information about the system provided by many sensors. From a practical point of view the cost of these sensors along with their maintenance would not be contemplated and so the fault detection system must cope with a list of more than one possible cause.

One possible method to help establish which of the list of potential alternatives has caused the system failure is to consider a probability for each component and to deduce which is the most likely failure cause combination. This addition to the procedure would require the calculation of importance measures [29] for each failure combination.

4.5.3.5 Dynamic Effects

At present for the water tank system the consistency checks are considered at the point the system is immediately observed. Due to this, it is not possible, since it does not take into account transient effects, for some of the 16 scenarios to occur. For example, none of the four schemes described have been able to correctly identify the potential causes of failure for scenarios 13 and 14 in the ACTIVE operating mode, as shown in Table 4.15. However, if dynamics were taken into consideration then depending on the state of the system these scenarios may occur, albeit for a short period of time.

As an example, when the system is ACTIVE and in scenario 13, all the sensor readings indicate a deviation from the expected sensor readings. Therefore there is 'NFTV1', 'NFTV2', 'FTV3' and 'WOST'. No flow at V2 can be caused by the valve itself failing closed, a blockage in pipe P3 or P4, a fracture in P3, the tank rupturing, or by a failure preventing water flowing into the system through V1. Combining the fault trees for both 'NFTV1' with 'NFTV2' and minimising the results leaves only the potential causes of failure caused by no flow at V1, making the results incorrect as in order for the system to be in scenario 13 there must be water in the tank because there is flow out at V3. Therefore no flow out at V2 cannot be the result of no water coming into the system at V1. However when the deviated sensor readings are combined and minimised using scheme 4 the potential causes of failure produced do not indicate that there is a failure preventing no flow at V2. This is an example of a situation where one failure has become hidden. A similar situation occurs in scenario 14. Taking account of, for example, the time it takes the water level to drop in the tank could help to overcome this problem. Therefore, considering the effects of dynamics on the water tank would provide a more realistic model of the system behaviour.

The validity of some of the results was found to be dependent upon the amount of water present in the tank. For instance scenario 16 in the ACTIVE operating mode could be caused by {{P1B}, {P1F}, {P2B}, {V1FC}, {C1FH}, {S1FH}, {NWMS}} if the water in the tank has been used up and no water has been allowed into the system to replenish that taken. This scenario could also be caused by {{P3B}, {P3F}, {P4B}, {V2FC}} if the level of water in the tank is as required and no water can exit the tank. A similar ambiguous situation occurs for scenario 8 in the ACTIVE mode. Taking into consideration transient effects in the system would help to alleviate this problem.

Some failures are dormant failures and may occur in the system and never be revealed until that part of the system is used or tested. For example, a blockage in pipe P5 would cause no flow through valve V3, but this would not become apparent until the safety part of the system was required, as shown in results from the simulation in Chapter 5. These types of failures will not be highlighted until that part of the system is used. This indicates that the fault detection system may need to consider revealed and dormant failure modes in different ways. Other failures may occur whilst a component is working as expected for a particular mode and only become visual when the expected operation for the component is changed. For instance, in ACTIVE operating mode valve V2 could fail open, but this failure would not become apparent until the the operator tried to close the valve to put the system in the DORMANT mode.

At present the two operating modes each have only one expected model of system behaviour as all monitored variables have only two discrete states; scenario 4 and 16 for the ACTIVE and DORMANT modes respectively. Taking dynamics in the tank into consideration these models will need to consider the actual value of the sensed variable, for example flow rate. The model will then need to account for the level of water in the tank and the rate of change of its height.

4.5.3.6 Two Phased System

The water tank system is assumed to be in one of two phases; these being the flow phase through valve V2 when in the ACTIVE operating mode and the no flow phase through V2 in the DORMANT operating mode. However, V2 could be partially open indicating an intermediate flow phase through the valve. Further analysis could therefore consider the behaviour of the system with partial failure modes.

4.6 Summary

- This chapter has introduced four fault tree based schemes for detecting faults or combinations of faults in systems.
- Fault tree analysis can be used to identify multiple faults in a systems fault diagnostic capability for steady state.
- Each scheme is demonstrated using the water tank level control system example and a brief comparison of results is made.
- Scheme 1 uses coherent fault trees to develop the causes of sensor readings. This method has been found to yield unreliable results because the fault trees do not contain enough information about the behaviour of the system. Also the method only considers the sensors that are not reading true to the operating mode, therefore causing more inaccuracies.
- A consistency check is introduced into scheme 2 by including information from all sensor readings obtained from the analysis. However, as shown in scheme 1 coherent fault trees do no contain enough information about the behaviour of the system to obtain a reliable list of potential causes. Scheme 2 uses the same fault trees, so invalid results can still occur.

- The system is modelled using non-coherent fault trees in Scheme 3. The introduction of NOT logic into the fault trees indicates which components are working for each of the deviated sensor readings and removes any conflicting potential causes. As in scheme 1 only sensor readings that have deviated from the normal system operating mode are taken into consideration in the analysis, therefore it does not include a consistency check.

- Non-coherent fault trees to represent the causes of sensor outputs provide more reliable results compared with those obtained using the coherent fault trees.

- The introduction of consistency checks with the information provided by all sensors is required in order to produce an accurate list of all potential causes of the current system state.

- Scheme 4 (II) uses non-coherent fault trees and includes both deviated sensor readings and those that are true to the operating mode in the analysis. The method checks for consistency by using information from all the observation points, and is the most accurate of schemes 1 to 4 for modelling behaviour of the water tank system.

- System dynamics must be taken into consideration to improve the method and obtain more accurate results. The dynamics should include the calculation of the level of water in the tank from the volume flow rate and spill tray sensors along with the introduction of more discrete height categories. Also, the rate of change of height should be calculated and timing taken into consideration.

- It may be necessary to consider different approaches in the fault diagnostics method to reveal dormant failure modes of components.

- In applying the fault tree based diagnostics technique the system sensors as described are sufficient, without any additional complexity. In a real system additional sensors could be added in order to provide a more complete picture of its operating state. The level control sensors S1 and S2 could also be used.

Chapter 5

Development of a Simulation Model and Fault Detection Demonstration

5.1 Introduction

Four fault tree based schemes for detecting faults or combinations of faults in systems were introduced in Chapter 4. Each scheme was demonstrated using the water tank level control system. This chapter describes the development of a computer program to simulate the system and implement the four fault detection schemes.

The program has been coded in the *C* programming language and consists of two main parts. The first is a model of the water tank and its components as described in Section 4.2. The state of each component can be set and changes to operation (non-failures) and/or faults may be introduced at any point in time. The simulation of the system reacts to any changes introduced in similar way to a real water tank. For instance, if pipe P2 is set to 'blocked' then water will not flow into the tank, just as in a physical system with a blockage at this point.

System status is determined using readings provided by the flow sensors VF1, VF2, and VF3 situated after each of the three valves, and the overspill tray sensor SP1. Flow measurements obtained from the simulation are fed into the second part of the program that demonstrates the fault detection method. System diagnosis is obtained by comparing the actual sensor readings from the simulation to the expected model behaviour, which will differ depending on whether the system is in the ACTIVE or DORMANT modes.

Analysis is carried out for each of the four schemes that were introduced in Chapter 4. Sensor readings that have deviated from their normal operation should result in the indication of a failure within the system. All potential causes of failure obtained are listed for each scheme with the most likely cause(s) of failure.

5.2 Water Tank System Model

The volume of water held in the tank at time t is dependent upon the amount of water in the tank at time $t-1$ and the volume flow rate of water into and out of the tank at time $t-1$. This can be obtained using Euler Integration [79], which leads to an equation of the form: $x_k = x_{k-1} + \dot{x}_{k-1}.dt$. The volume flow rate into the tank system is calculated from the velocity of the inflow and the radius of pipe P2. The outflow depends on three factors: the amount of water exiting the tank through valves V2 and V3, and any leakages present within the walls of the tank. The volume flow rates at VF2, VF3 and water loss via a leak depends upon the head of water in the tank above their locations.

Water transition within the tank system is modelled with equations for the volume flow rate into and out of the tank along with the water height. The equations used are described in Sections 5.2.1 to 5.2.2.

5.2.1 Volume of Water in the Tank

5.2.1.1 Volume Flow Rate at Sensor VF1

The volume flow rate at VF1, $\dot{v}_1(t)$, at time t is assumed to be constant, therefore is expressed as:

$$\dot{v}_1(t) = A_1 u_1(t), \tag{5.1}$$

where A_1 is the cross-sectional area of pipes P1 and P2, and $u_1(t)$ is the velocity of flow into the tank at VF1 at time t.

5.2.1.2 Volume Flow Rate at Sensor VF2

The volume flow rate at VF2, $\dot{v}_2(t)$, at time t is expressed as:

$$\dot{v}_2(t) = A_2 u_2(t), \tag{5.2}$$

where, A_2 is the cross-sectional area of pipes P3 and P4, and $u_2(t)$ is the velocity of flow out of the tank at VF2 at time t. Using Torricelli's Law [80], $u_2(t)$ can be written as:

$$u_2(t) = \sqrt{2gh(t)}, \tag{5.3}$$

where g is acceleration due to gravity and $h(t)$ is the height of water in the tank at time t. The height of water in the tank can be expressed in terms of the volume of water in the tank and its cross-sectional area, A_T. Therefore, $h(t)$ can be written as:

$$h(t) = \frac{v(t)}{A_T}, \tag{5.4}$$

Equation 5.3 becomes,

$$u_2(t) = \sqrt{2g\frac{v(t)}{A_T}}, \tag{5.5}$$

Therefore Equation 5.2 can be expressed in terms of Torricelli's Law,

$$\dot{v}_2(t) = A_2\sqrt{2g\frac{v(t)}{A_T}}. \tag{5.6}$$

5.2.1.3 Volume Flow Rate at Sensor VF3

The volume flow rate at VF3, $\dot{v}_3(t)$, at time t can be expressed as:

$$\dot{v}_3(t) = A_3 u_3(t), \tag{5.7}$$

where, A_3 is the cross-sectional area of pipes P5 and P6, and $u_3(t)$ is the velocity of flow out of the tank at VF3 at time t. Assuming that pipes P3, P4, P5 and P6 are at the same height in the tank,

$$u_2(t) = u_3(t). \tag{5.8}$$

Equation 5.7 becomes,

$$\dot{v}_3(t) = A_3 u_2(t). \tag{5.9}$$

Also, if the cross-sectional area of both pipes P5 and P6, A_3, is twice that of pipes P3 and P4, A_2 (as flow out at V3 can be twice the amount out at V2), then,

$$A_3 = 2A_2. \tag{5.10}$$

Therefore, Equation 5.9 can be expressed as,

$$\dot{v}_3(t) = 2A_2 u_2(t). \tag{5.11}$$

Substituting for $u_2(t) = \sqrt{2g\frac{v(t)}{A_T}}$ gives,

$$\dot{v}_3(t) = 2A_2\sqrt{2g\frac{v(t)}{A_T}}. \tag{5.12}$$

5.2.1.4 Overspill Tray Sensor SP1

A leak in the tank system has been modelled assuming that the height and cross-sectional area of the leak are known. The size of the leak can be varied by changing the cross-sectional area, and the effect of the location of a leak investigated by changing the height at which it is situated.

The volume flow rate out at a leak, $\dot{v}_4(t)$, at time t can be used to calculate the amount of water in the overspill tray, as indicated by sensor SP1. This can be expressed as:

$$\dot{v}_4(t) = A_4 u_4(t), \tag{5.13}$$

where, A_4 is the cross-sectional area of the leak and $u_4(t)$ is the velocity of flow out of the tank at the leak at time t. In order to calculate $\dot{v}_4(t)$ the height of water above and below the leak has to be considered. The height of water in the tank can be expressed as:

$$h(t) = j(t) + k(t),$$

where, $j(t)$ is the height of water above the leak in the tank and $k(t)$ is the height of water below the leak, as shown in Figure 5.1. The volume flow rate out of the leak will be dependent upon the head of water above it.

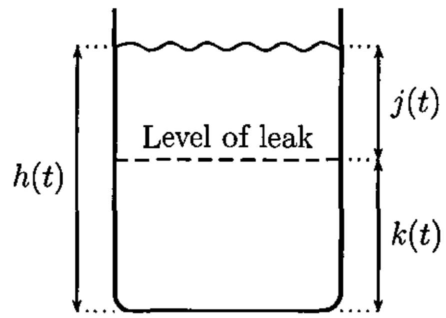


Figure 5.1: Water tank heights for an example leak

The velocity $u_4(t)$ can be expressed as:

$$u_4(t) = \sqrt{2gj(t)}, \tag{5.14}$$

where, $j(t) = h(t) - k(t)$. Once the level of water in the tank drops below the hole that is causing the leak, flow out from it will cease and so $j(t) = 0$ (therefore $h(t) = k(t)$). Also if the leak is located at the bottom of the tank then $k(t) = 0$, hence $h(t) = j(t)$.

The height of water above the leak in the tank can be expressed in terms of the volume of water above the leak and the cross-sectional area. Therefore the height $j(t)$ can be written as:

$$j(t) = \frac{v_j(t)}{A_T},$$

where $v_j(t)$ is the volume of water in the tank at time t for the height j.

Equation 5.14 becomes,

$$u_4(t) = \sqrt{2g\left(\frac{v_j(t)}{A_T}\right)}.$$

Therefore, substituting this into Equation 5.13 gives:

$$\dot{v}_4(t) = A_4\sqrt{2g\left(\frac{v_j(t)}{A_T}\right)}. \tag{5.15}$$

5.2.2 Equation for Volume of Water in the Tank

The volume of water in the tank at time t can be found using Euler Integration [79]:

$$v(t) = v(t-1) + \left[\dot{v}_1(t-1) - (\dot{v}_2(t-1) + \dot{v}_3(t-1) + \dot{v}_4(t-1))\right] dt, \tag{5.16}$$

where $\dot{v}_1(t-1)$, $\dot{v}_2(t-1)$, $\dot{v}_3(t-1)$ and $\dot{v}_4(t-1)$ are the flow rates at VF1, VF2, VF3 and SP1 respectively, at time $t-1$, and dt is the time increment.

Substituting equations 5.1, 5.6, 5.12 and 5.15 into 5.16 gives:

$$v(t) = v(t-1) + \left[A_1 u_1(t-1) - \left(3A_2\sqrt{2g\frac{v(t-1)}{A_T}} + A_4\sqrt{2g\frac{v_j(t-1)}{A_T}}\right)\right] dt. \tag{5.17}$$

5.2.3 Equation for Height of Water in the Tank

The height of water in the tank at time t can be expressed in terms of the volume of water in the tank, and the tank's cross-sectional area, as shown in Equation 5.4. Substituting

Equation 5.17 into Equation 5.4 gives:

$$h(t) = \frac{v(t-1) + \left[A_1 u_1(t-1) - \left(3A_2\sqrt{2g\frac{v(t-1)}{A_T}} + A_4\sqrt{2g\frac{v_j(t-1)}{A_T}}\right)\right] dt}{A_T}. \quad (5.18)$$

The rate of change of the height of water in the tank can also be obtained using Equation 5.4:

$$\frac{dh(t)}{dt} = \left[A_1 u_1(t-1) - \left(3A_2\sqrt{2g\frac{v(t-1)}{A_T}} + A_4\sqrt{2g\frac{v_j(t-1)}{A_T}}\right)\right] A_T.$$

5.3 Fault Detection Demonstration

This section describes the construction of the water tank simulation and fault tree capability. Figure 5.2 illustrates how the data flows between the fundamental elements of the simulation and these are described in more detail in Section 5.3.1 to 5.3.5.

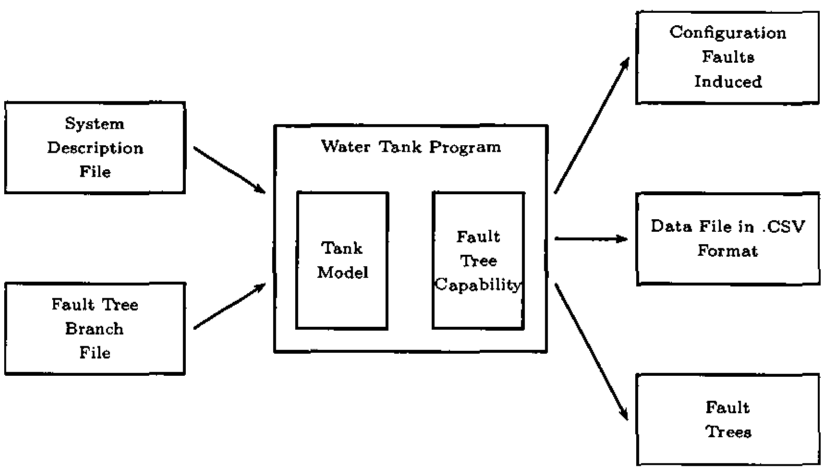


Figure 5.2: Data flow between major components of water tank simulation

Information regarding the system status is input into the simulation through the system description and fault tree branch files. This will update the system behaviour and then any deviations obtained are used in the fault tree capability. The system outputs a file containing the system configuration and any faults induced in the system, also system data from the simulation and any potential failures present. More information regarding the input and output files for the system are shown in Appendix B.

The following list contains an overview of how the program works:

- Changes to the system tank model status and the fault trees are input into the program.
- The changes made to the system are output to a file.
- The simulation is executed for a given amount of time steps.
- At each print step information from the system is output to a file.
- The actual and expected sensor readings are compared at each check step for the given mode of operation.
- A scenario for the system is identified.
- A TOP event structure is constructed for the identified system scenario for each of the four schemes.
- Cut sets/prime implicants are obtained and minimised.
- The coherent approximation is performed and the list of potential causes for each scheme re-minimised.
- The potential causes of failure for each scheme are output to a file.
- The most likely cause of failure is ascertained through the use of importance measures.

The water tank simulation has been verified as representative of a real system by the comparison of its results against those results identified for each of the schemes using FaultTree+. These have also in turn been compared to those expected, which were identified by hand. More information regarding the use of FaultTree+ and the identification of actual possible causes of failure can be found in Chapter 4.

5.3.1 Input Parser

The input parser processes the contents of the system description file and the fault tree branch file. It tokenises each line, removing spaces and commas. For instance, an input line in the system description file could be 'VALVE1 STATE FAILEDOPEN 0.00' and this becomes 'VALVE1' 'STATE' 'FAILEDOPEN' '0.00'.

The program parses the tokens of each of these files to check if each line input is a representative of a valid state change, variable assignment or random failure. If the tokens do not form a valid statement an error is generated informing the user of the number of the invalid line.

5.3.2 Simulation Model

The model of the water tank system is represented using a series of *C* data structures. Each structure contains information about a particular system component. Figure 5.3 is a simplified class diagram showing the attributes of components within the model.

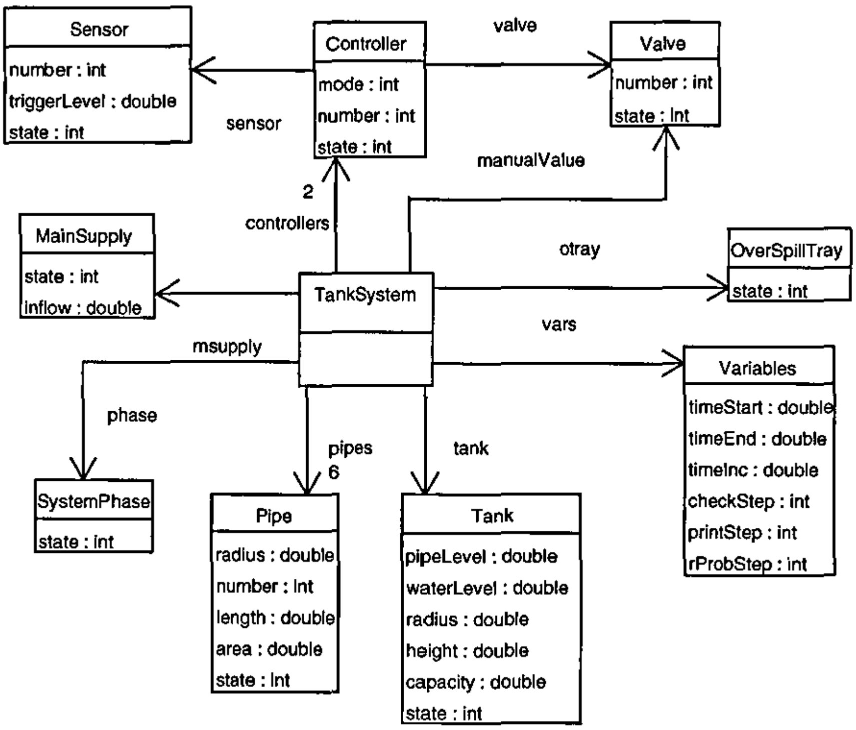


Figure 5.3: Class diagram showing the component attributes

Each component has attributes defined by a structure with associated functions declared in a corresponding module. For instance, a pipe structure has attributes number, length, radius, state and area. Functions that operate with the pipe include 'pipeInit()', 'pipeSetstate()' and 'pipeWaterCanFlow()'.

The level control in the simulation takes into account the state of the components that direct the flow of water. These are namely the control loop containing valve V1, controller C1 and sensor S1 for water flowing into the tank and the loop with valve V3, controller C2 and sensor S2 controlling the amount of water leaving the tank through the safety valve.

When the components are working normally the sensors will indicate that the water level is as required. Flow into the system will occur when the level sensors are reading low and C1 in this case will keep V1 open to allow the water level to be replenished. If the sensors indicate a high level of water C2 will open V3 in an attempt reduce this.

If either of the controllers has failed the simulation will ignore the reading from the corresponding level sensor and will instruct the appropriate valve to open or close based on the failed state. Likewise a failed valve will ignore requests from the controller to open or close as required and continue in its current state.

Within the simulation each controller has been given a mode to enable the same code to be used to model both. The mode allows them to take different actions depending on the readings from the sensors. C1 is said to be in an 'inverted mode' so will keep V1 open when the sensors are low. C2 is in a 'normal mode', therefore opens V3 when the sensors are reading a high water level.

5.3.3 State Change Mechanism

The state change mechanism causes changes to the states of the model's components either by user request or random generation via the system description file. Each change occurs at the end of the time interval at which it is stated to start from. The name of the component to be changed, a new state for the component and an optional time for this change to take place is required to cause the occurrence of a change in state. All changes are sorted and stored in order of time and component, and these are output to the configuration file as described in Section B.3.1.

5.3.4 Main Loop of the Simulation

At the core of the simulation is a 'loop' that iterates from the start to end time of the analysis. At each time step the current time is increased by the time increment *dt*. A flowchart illustrating the operations performed by the main loop is shown in Figure 5.4.

Before the loop commences the time variables are initialised and state changes that have been set to occur at the start are induced. After this intialisation the current time is incremented and the program enters a *while* loop that cycles whilst the current time is less than or equal to the end time.

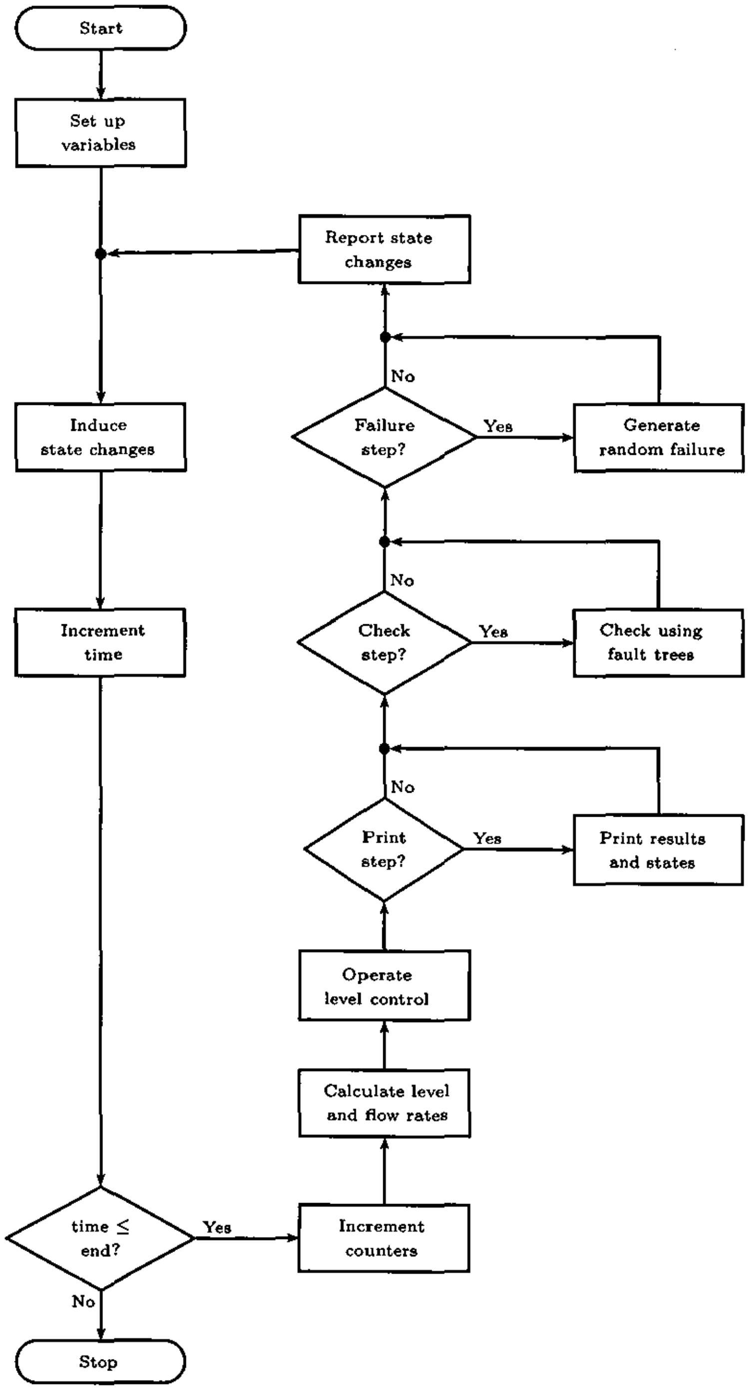


Figure 5.4: Flow Chart for the main loop of the water tank simulation

The first time point to involve any calculation is the 'start time $+dt$'. For this and every increment until the end time the body of the loop is executed. Each time round the loop the counters for the print, check, and random failure time steps are incremented. The level and flow rates are then calculated and the controllers are operated depending on the readings from the level sensors throughout the system operation. The print and check counters within the system are then compared to see if they indicate the need to output data or check for failures.

In order to constantly monitor for failures, the program has been set to check the sensor readings for any deviations at every time step. Before the next iteration commences the state changes are applied to the current time step and written out to the configuration file. The value of the current time step is incremented by dt and the loop iterates again.

5.3.5 Fault Tree Capability

The identification of the potential causes of failure and the prediction of the most likely cause, when there is more than one possibility, is conducted in the second part of the program. This section uses the sensor readings for VF1, VF2, VF3 and SP1 along with the identification of the system operating mode that are supplied by the simulation model.

The failure logic diagrams produced for the water tank system represent the causes of any sensor readings and are outlined in Chapter 4, Section 4.3. The trees for each sensor reading are input into the program and used when indicated by the given system scenario. All possible causes of a scenario are obtained by constructing a TOP event structure from the information given by the observation points within the system. The fault trees for the obtained sensor readings are combined using an AND gate. The program constructs a TOP event structure for each of the four schemes described in Section 4.4 to illustrate their individual results. In the event that the system is working as required no fault tree will be generated for schemes 1 and 3 as these do not take into consideration consistency.

5.3.5.1 Fault Tree Generation

The fault trees are represented in the program's code using an 'n-tree structure'. Each tree node can contain up to n branches. The structure is illustrated in Figure 5.5. Basic events in the fault trees are built into the code as 'terminal nodes' and each of these has a 'component name' and 'state'. Intermediate events are represented by 'non-terminal nodes' and each has a related AND, OR or NOT gate. A NOT gate will only ever contain a single branch. The coherent and non-coherent fault trees for each of the deviated sensor readings are loaded from the fault tree branch file and this information is used to generate the fault trees.

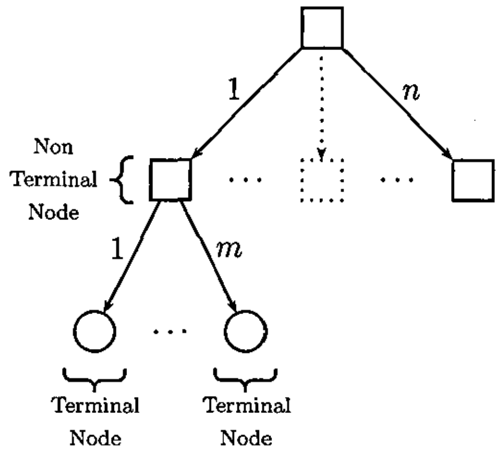


Figure 5.5: Fault tree structure

5.3.5.2 Combining of Fault Trees for Given Sensor Readings

At any given time the sensors must indicate one of the 16 scenarios listed in Chapter 4, Table 4.1. If the system is ACTIVE the sensors should show the readings listed in scenario 4 of Table 4.1. When the system is DORMANT sensor readings should correspond to scenario 16. When the readings do not match the model behaviour it suggests a fault exists in at least one of the system components. Potential causes of system failure can be obtained by constructing a top event structure from the information provided by VF1, VF2, VF3 and SP1. A top event structure can be constructed from 0 (if there are no failures) to 4 (if all sensors fail or consistency checks are used) sensor readings, depending on the scenario, phase and scheme. Fault trees for the sensor readings are combined to form a top event structure for the scenario using an AND gate. This fault tree is built by the program and output to the fault file (see section B.3.3). Figure 5.6 illustrates how the status of each sensor is used to form the TOP event structure.

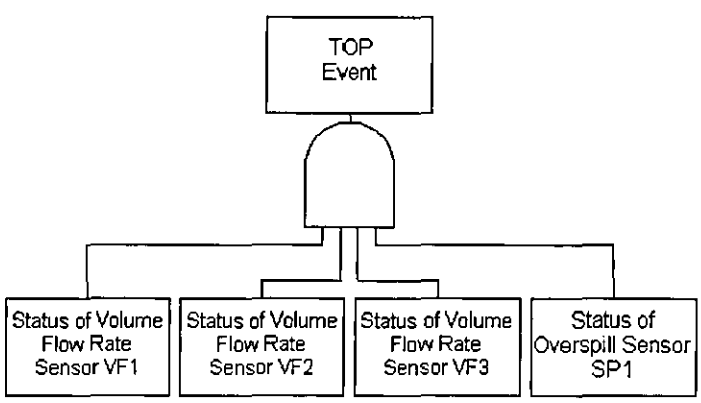


Figure 5.6: Typical TOP event structure built by the water tank simulation program

5.3.5.3 Cut Set Extraction

Cut sets are obtained for the given sensor readings by recursively traversing the fault trees and applying the operations described by the non-terminal nodes. A cut set is made up of terminals, which represent the basic events in the program code. Each cut set is represented using a non-balanced 'binary-search-tree' structure. Sets of cut sets are represented using a dynamic array, each element of which is a pointer to a cut set's binary search tree, as illustrated in Figure 5.7. This dynamic array consists of n cut sets for a given fault tree. The first cut set in the example (entry 0 in the array) is of order two and the second (entry 1) of order three.

Each of the terminals in these cut sets would have a component name, state and negated flag (to indicate a working component). Using the binary tree structure means that a terminal can appear at most once in each cut set, which aids the minimisation procedure. A cut set may appear more than once in the dynamic array, however in each cut set there will not be any repeated component failures. Any branches of the fault tree that are negated can also be recursively traversed, the cut sets extracted, minimised and placed into the dynamic array along with the rest of the cut sets.

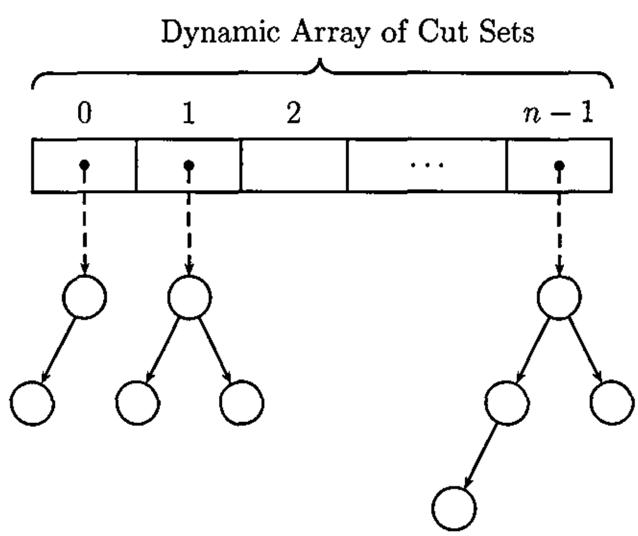


Figure 5.7: Structure of binary search trees in the dynamic array

5.3.5.4 The Minimisation Procedure

The first part of the minimisation procedure occurs when the cut sets are extracted and placed into the dynamic array. The second part of the procedure process involves removing any cut sets from the dynamic array that are not minimal. Each cut set is compared with each other to ensure that no cut set is a subset of or exactly the same as another.

For two cut sets A and B, if $A \subseteq B$ where A contains fewer elements than B then cut set B would be removed from the list. Also, there is the possibility that $A = B$, so in this case one of the copies of the same cut set will be removed. The removal of duplicated cut sets is implemented using a similar procedure to that used by the MOCUS algorithm [29]. The time complexity of the algorithm is non-linear and therefore a more efficient solution to minimisation needs to be found. This does however limit the use of this software in a real time application, and therefore a more efficient solution to minimisation needs to be found.

5.3.5.5 The Coherent Approximation Procedure

Some of the cut sets in the dynamic array may contain negated terminals. Once the cut sets have been extracted and minimised for the dynamic array, the negated terminals from the sets may be removed. Minimisation takes place again as the cut sets may no longer be minimal. This procedure ensures that all minimised cut sets are only made up from potential causes of failure and not working state modes.

5.3.5.6 Measures of Importance

In the majority of cases more than one potential cause of failure will be obtained, as discussed in Section 4.5.3.4 and shown from the results obtained. In order to deduce the most likely outcome reliability theory can be utilised to rank the potential failure causes obtained. The unavailability for each component failure is given by Equation 3.35. Is has been assumed that the repair rate is 0. The Fussell-Vesely measure of minimal cut set importance [29] is used to rank the cut sets obtained from the analysis and is shown in Equation 3.49. Q_{SYS} in this equation is calculated using the Rare Event approximation, as shown in Equation 3.45.

5.4 Simulation Results

There are three ways in which failures can be generated for the water tank system: through manually inducing a failure at a specified point in time for a selected component, by randomly generating a specified number of components to fail at a given point in time, or through use of the unavailability of each component (See Appendix B).

Example Induced System Failure

The first example shows the results obtained for a failure induced into the system at a specific point in time. A component state change can be induced at any specified time in the simulation and does not necessarily have to be a system failure. For instance, the system can be switched to ACTIVE from DORMANT at a specified time without a failure taking place.

Two failures - sensor S2 fails high (S2FH) and tank leaks (TL) - were induced into the system at the same time in the ACTIVE operating mode. The simulation identified that there was flow leaving the system at VF3 and water was detected in the overspill tray at SP1, indicating that the system was in scenario 1 in Table 4.1. There were 102 potential causes of failure identified using scheme 1 in this case. However, only 15 of these were actually valid for the top event. The potential causes of failure obtained for each of the four schemes are listed in Table 5.1.

	Results from Scheme 1		Results from Scheme 2		Results from Scheme 3		Results from Scheme 4		
	Valid Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Actual Possibilities
1)	S2FH.TL	S2FH.TL	S2FH.TL	S2FH.TL	S2FH.TL	S2FH.TL	S2FH.TL	S2FH.TL	S2FH
2)	C2FH.TL	C2FH.TL	C2FH.TL	C2FH.TL	C2FH.TL	C2FH.TL	C2FH.TL	C2FH.TL	C2FH
3)	V3FO.TL	V3FO.TL	V3FO.TL	V3FO.TL	V3FO.TL	V3FO.TL	V3FO.TL	V3FO.TL	V3FO
4)	V1FO.P3B.TL				V1FO.P3B.TL				
5)	V1FO.P3F.TL				V1FO.P3F.TL				
6)	V1FO.P4B.TL				V1FO.P4B.TL				
7)	V1FO.V2FC.TL				V1FO.V2FC.TL				
8)	S1FL.P3B.TL				S1FL.P3B.TL				
9)	S1FL.P3F.TL				S1FL.P3F.TL				
10)	S1FL.P4B.TL				S1FL.P4B.TL				
11)	S1FL.V2FC.TL				S1FL.V2FC.TL				
12)	C1FL.P3B.TL				C1FL.P3B.TL				
13)	C1FL.P3F.TL				C1FL.P3F.TL				
14)	C1FL.P4B.TL				C1FL.P4B.TL				
15)	C1FL.V2FC.TL				C1FL.V2FC.TL				

Table 5.1: Results obtained for schemes 1 to 4 when the system is induced with the failure V2FC.TL in the ACTIVE operating mode

Only the potential causes valid (those that can actually occur) for the given top event obtained in scheme 1 are shown. The most likely cause of failure obtained using Fussell-Vesely measure of minimal cut set importance measure was found to be S2FH.TL, which in this case is correct. However, this measure may not always be this accurate. For instance, the same most likely cause of failure would have occurred if valve V3 had failed open and the tank could leak resulting in the same scenario.

Example Random Failure

The random component failure feature is enables the generation of a fixed number of random component failures at a specified time. Any failures in the system may not always have an immediate effect on the system functionality. For example, a failure randomly induced into the system was valve V1 failing closed (V1FC) at time t = 120s in the DORMANT operating mode. In this case the fault was not detected by the fault tree capability for any of the four schemes because valve V1 is expected to be closed in this mode. Therefore it would not be indicated until the system became ACTIVE or through a change in scenario. This highlights a restriction in the analysis.

Example Failure Based on Unavailability

Valve V3 fails open (V3FO) was an example failure input into the system depending upon the unavailability of each component. The fault was detected by the fault tree capability for each of the four schemes, the results from which are listed in Table 5.2.

	Results from Scheme 1		Results from Scheme 2		Results from Scheme 3		Results from Scheme 4		
	Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Obtained Potential Causes	Correct Potential Causes	Actual Possibilities
1)	S2FH	S2FH	S2FH	S2FH	S2FH	S2FH	S2FH	S2FH	S2FH
2)	C2FH	C2FH	C2FH	C2FH	C2FH	C2FH	C2FH	C2FH	C2FH
3)	V3FO	V3FO	V3FO	V3FO	V3FO	V3FO	V3FO	V3FO	V3FO
4)	V1FO.P3B				V1FO.P3B				
5)	V1FO.P3F				V1FO.P3F				
6)	V1FO.P4B				V1FO.P4B				
7)	V1FO.V2FC				V1FO.V2FC				
8)	S1FL.P3B				S1FL.P3B				
9)	S1FL.P3F				S1FL.P3F				
10)	S1FL.P4B				S1FL.P4B				
11)	S1FL.V2FC				S1FL.V2FC				
12)	C1FL.P3B				C1FL.P3B				
13)	C1FL.P3F				C1FL.P3F				
14)	C1FL.P4B				C1FL.P4B				
15)	C1FL.V2FC				C1FL.V2FC				

Table 5.2: Results obtained for schemes 1 to 4 for the occurrence of V3FO through unavailability in the ACTIVE operating mode

At each specified time step within the analysis the components are checked for failure and for the type of failure that has occurred. The system scenario are determined to be number 2 in Table 4.1. The most likely cause of failure obtained using Fussell-Vesely measure of minimal cut set importance measure was found to be S2FH, which in this case is incorrect, however, this failure is in the list of possibilities identified.

5.5 Summary

- This chapter has described the development of a computer program to simulate the system and implement the four fault detection schemes introduced in Chapter 4.
- The program consists of two main parts. The first is a model of the water tank and its components. The second part of the program demonstrates the fault detection method.
- System status is determined using readings provided by the flow sensors VF1, VF2 and VF3 situated after the three valves, and the overspill tray sensor SP1.
- Component state changes can be induced to occur at a specific point in time, randomly or depending on the unavailability.

Chapter 6

Consideration of Dynamics

6.1 Introduction

Chapter 4 contained a discussion of the results obtained for the four fault tree based schemes that were described. It was found that scheme 4, which uses non-coherent fault trees, and checks for consistency by using information from all the observation points is the most accurate at modelling system behaviour.

An important issue highlighted was the need to consider dynamics in the analysis in order to improve the method and obtain more accurate results. Transient effects are now discussed in more detail in this Chapter. This will include investigating time history, rate of change of height and the level of water in the tank. The simple water tank level control system introduced in Chapter 4 is used to demonstrate the dynamic features of the method. The system has two operating modes, these being ACTIVE and DORMANT, each of which identify the expected system behaviour depending on the exact flow of water in and out of the system.

Another factor to consider is the scalability of the method and how well it could be applied to a larger system. The size and number of fault trees analysed will need to be reduced when used on a bigger system. In addition bounds are required on the fault tree development to restrict the causal relationships to those of the control systems on each stream. The results in Chapter 4 showed that a consistency check is required to produce an accurate list of potential causes of system failure. The use of a check against those parts of the system known to be working in the dynamic method is also considered in this chapter.

6.2 System Stages

The fault detection and identification process is performed in two stages. The first is the modelling and preparation stage, during which information required concerning the causes and consequences of failures in the system's sections is gathered. This information is stored and used in the application stage to identify component failures that cause the observed symptoms. The stages are described in more detail in Sections 6.2.1 and 6.2.2 respectively.

6.2.1 System Modelling and Preparation Stage

The modelling and preparation stage is the part of the analysis in which all available information about a given system is collected and used in preparation for application.

1. The first task is to divide the system up into sections or subsystems. These should be parts of the system that can change the process variables by either normal control action or through the occurrence of a component failure.

2. The subsystem process variables that are to be measured, such as flow, temperature, pressure or level are identified. Sensors can then be incorporated into the system in order to monitor these variables if not already present for control purposes.

3. All the possible modes of system operation are identified. Assumptions to be made that can affect the operation of the system are also listed.

4. All system scenarios are developed. The scenarios consider all possible deviations in the process variables on each section. They may be failed high, low or be working as normal. On sections where there is a control system, the deviations may be due to control system failures. Deviations can also occur due to the failure of passive components such as pipes or wires. Some sections may contain only passive elements of the system in which case changes in the related process variable will only happen when a failure mode occurs or changes in section inputs and outputs.

5. For each of the system operating modes identified, a set of potential patterns from the readings obtained from each section are developed. Only the shape of the sensor reading pattern is required.

6. Fault trees for causes of the process variable deviation at each of the sensor locations used to define the scenarios are drawn. Each fault tree is developed down to the

component failures in the system. Fault trees may be drawn for absolute values or rates of change, depending on what information is considered useful for the particular system. For any normal system behaviour causes of sensor readings are developed using success trees, which describe all the components in the system that must be working correctly in order for that outcome to occur.

These stages are now demonstrated using the water tank system.

6.2.1.1 System Division

The water tank system can be split into five sections as shown in Figure 6.1. Each section is indicated in the diagram by the dashed lines, three of which contain a valve, the fourth includes the tank along with its level and the fifth section contains the overspill tray.

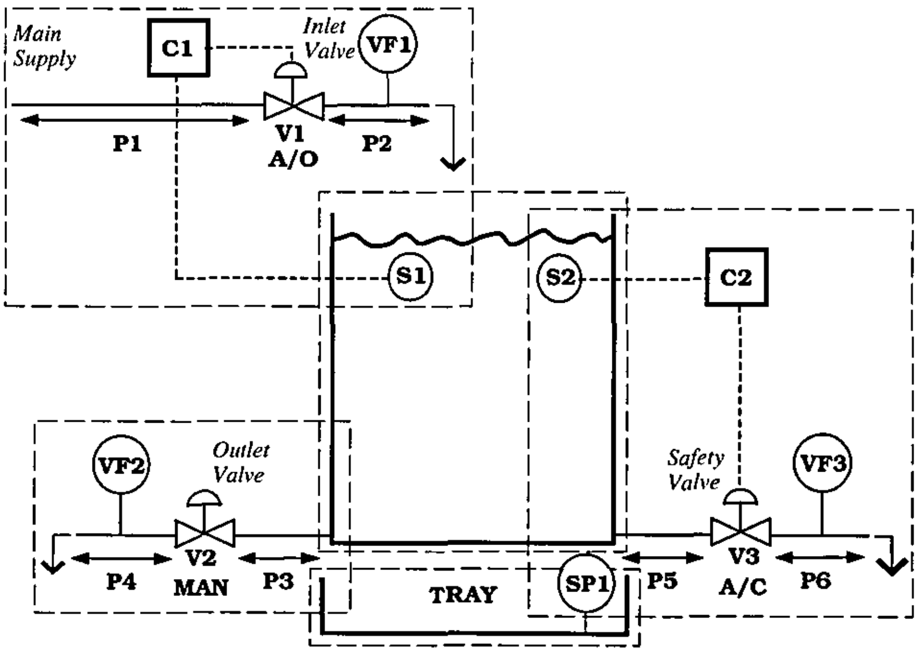


Figure 6.1: Water tank system sections

6.2.1.2 Identification of System Sensors

The flow in and out of the system is observed using 3 flow sensors that are situated next to each valve to measure the flows, as described in Chapter 4. The sensors are denoted by VF1, VF2, VF3 for the locations V1, V2 and V3 respectively (see Figure 6.1 for an illustration of the water tank system). It is now assumed that each of these sensors can measure the exact flow rate at their particular location in the system. A fourth sensor SP1 is located in the overspill tray (TRAY) to detect if there is any loss of containment of water in the tank.

6.2.1.3 Identification of Process Variables

The overall aim of the system is to control the water level in the tank, therefore this is the key system variable in this example. The flows in and out of any part of the system are dynamic factors that affect the level of water in the tank, which can be calculated from the measurements taken by the 4 sensor readings and also obtained directly from the level sensors S1 and S2. The height of water is now considered in 6 discrete categories: empty (E), low (L), normal (N), high (H), very high (VH) and full (F), as shown in Figure 6.2. The tank is expected to stay within the 'normal' level threshold under normal operating conditions.

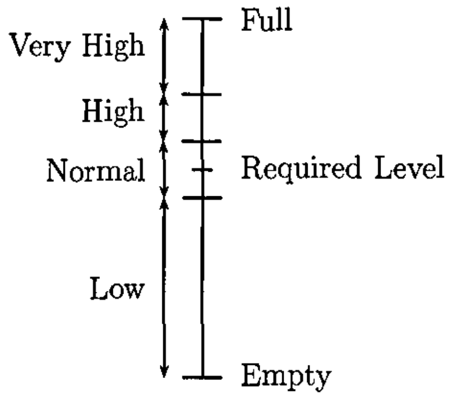


Figure 6.2: Discrete height categories

The system will start out at the normal level, which it aims to maintain throughout the operation. If any other level is obtained this indicates that a failure of some kind has occurred in the tank system. For instance, an empty or low water level implies that there has been more flow out of the system than is going in. In this case, flow in would be expected in order to try and replenish the system. A high level is caused by more flow into the system than out and indicates that the level is over the normal threshold in the tank. If the level becomes very high or full the safety valve would normally operate in an attempt to reduce the water level.

6.2.1.4 System Scenarios

The valves at the sensors VF1, VF2 and VF3 can be working (WK), be providing unrequired or high flow (HF) or not allowing flow when needed, resulting in 'low flow' (LF). The conclusion that a control valve system is working indicates that the valve at this point is opening and closing as and when required by the system, therefore providing flow and no flow on demand for the chosen operating mode. If high flow occurs one of the valves is causing uncontrollable water flow into or out of the system. Low flow will result in uncontrollable no flow occurring, therefore at this point in the system there is no water flow when required. The two latter possibilities are the result of a failure occurring somewhere in the system. The sensor in the overspill tray SP1 can indicate that the tank is working (WK), or that a failure has occurred causing water to accumulate in the tray (TF). From the flow sensors at V1, V2, V3 and in the TANK there are 54 different potential scenarios that can possibly occur, as listed in Table 6.1.

Scenario	V1	V2	V3	TANK
1	WK	WK	WK	WK
2	WK	WK	WK	TF
3	WK	WK	HF	WK
4	WK	WK	HF	TF
5	WK	WK	LF	WK
6	WK	WK	LF	TF
7	WK	HF	WK	WK
8	WK	HF	WK	TF
9	WK	HF	HF	WK
10	WK	HF	HF	TF
11	WK	HF	LF	WK
12	WK	HF	LF	TF
13	WK	LF	WK	WK
14	WK	LF	WK	TF
15	WK	LF	HF	WK
16	WK	LF	HF	TF
17	WK	LF	LF	WK
18	WK	LF	LF	TF
19	HF	WK	WK	WK
20	HF	WK	WK	TF
21	HF	WK	HF	WK
22	HF	WK	HF	TF
23	HF	WK	LF	WK
24	HF	WK	LF	TF
25	HF	HF	WK	WK
26	HF	HF	WK	TF
27	HF	HF	HF	WK

Scenario	V1	V2	V3	TANK
28	HF	HF	HF	TF
29	HF	HF	LF	WK
30	HF	HF	LF	TF
31	HF	LF	WK	WK
32	HF	LF	WK	TF
33	HF	LF	HF	WK
34	HF	LF	HF	TF
35	HF	LF	LF	WK
36	HF	LF	LF	TF
37	LF	WK	WK	WK
38	LF	WK	WK	TF
39	LF	WK	HF	WK
40	LF	WK	HF	TF
41	LF	WK	LF	WK
42	LF	WK	LF	TF
43	LF	HF	WK	WK
44	LF	HF	WK	TF
45	LF	HF	HF	WK
46	LF	HF	HF	TF
47	LF	HF	LF	WK
48	LF	HF	LF	TF
49	LF	LF	WK	WK
50	LF	LF	WK	TF
51	LF	LF	HF	WK
52	LF	LF	HF	TF
53	LF	LF	LF	WK
54	LF	LF	LF	TF

Table 6.1: System Scenarios

The working state includes situations where a failure has occurred on a component causing a valve to operate in a certain way to try and rectify the problem. For instance, if the level of water in the tank rises too high the safety valve is expected to open. This indicates that a failure has occurred in the system, but this valve has acted correctly in order to rectify the problem. Any drop in the level of water in the tank will cause valve V1 to open and this will stay open until the level is replenished, regardless of the system operating mode, as the level of water in the tank is always expected to be normal.

6.2.1.5 Modes of System Operation and System Assumptions

6.2.1.5.1 Modes of System Operation

The water tank's two modes of operation are ACTIVE and DORMANT. If ACTIVE, water is taken out of the tank through valve V2 and replaced by water coming into the system through V1 from the main supply. There is no flow out of V3 and no water exiting the tank to the overspill tray. When in the DORMANT mode valves V1, V2 and V3 would remain closed and the overspill tray would be empty.

Taking dynamics into consideration, if the system is ACTIVE then in addition to flow in at V1 and flow out at V2 a 'normal' water level will be expected. The level of water in the tank may fluctuate but should not rise above or fall below the normal threshold shown in Figure 6.2. In the DORMANT operating mode the level of water in the tank is expected to again be 'normal', with zero rate of change.

6.2.1.5.2 System Operating Assumptions

In addition to the assumptions made in Chapter 4:

- Originally it was assumed that a rupture in the tank would cause no flow out of any of the valves in the system. However it would take time for the tank to empty and this is now identified in the analysis.
- Flow out at the subsection containing valve V2 or V3 and a leak in the tank cannot be compensated for by flow into the system.

6.2.1.6 Potential Patterns

The flow rate measurements taken from the sensors VF1, VF2, VF3 and SP1 can be used to build up a flow rate history at these particular locations in the tank over a period of time. From these a pattern of the history can be identified and used to obtain a list of scenarios that the system can potentially be in from the 54 possibilities listed in Table 6.1.

The level of water in the tank and the rate of change can be calculated from the readings. In a similar way as described for the sensors these two pieces of information can be used to build up a history of the level of water in the tank over a period of time. Tables 6.2 and 6.3 show the expected patterns for the system when in the ACTIVE and DORMANT operating modes respectively.

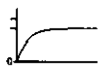
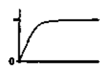
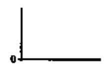
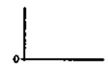
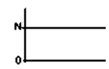
Scenarios	V1	V2	V3	TANK	Level
1, 5, 7, 11, 19, 23, 25, 29					

Table 6.2: Expected readings when the system is in the ACTIVE operating mode

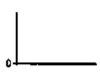
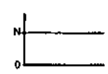
Scenarios	V1	V2	V3	TANK	Level
1, 5, 13, 17, 37, 41, 49, 53					

Table 6.3: Expected readings when the system is in the DORMANT operating mode

Each table indicates patterns in the sensor readings taken over a period of time from the start of the current operating mode, i.e. from when the system became ACTIVE or when it became DORMANT. These are for the four locations in the system, indicating the amount of flow at the volume flow rate sensors and the amount of water in the overspill tray. The level pattern illustrates how the reading has changed over time, from which the rate of change can be determined. Any pattern of results that is different from those set out for the system in the ACTIVE and DORMANT operating modes will indicate that a failure must have occurred somewhere in the system. Failure conditions within the system can exist at the start of and may also occur during an operation.

There are a number of scenarios for the system that indicate the expected system behaviour when in the ACTIVE operating mode, as listed in Table 6.2. Scenario 1 however, is the only one where the system is working correctly producing the 4 given sensor readings and level pattern. The remaining 7 possibilities all contain an unrevealed failure of some kind whose symptoms are masked. Flow in and out of the system could be occurring as expected, but there could still be a hidden failure somewhere in the system. A way of checking the system for unrevealed failures would be to switch the operating mode from ACTIVE to DORMANT. In this case failures in scenarios 7, 11, 19, 23, 25 and 29 would become apparent. Failures would not be identified in scenario 5, which indicates a problem at valve

V3, unless the level of water in the tank rises to or above very high, at which point the safety valve should open. Similarly any failure linked to V3 in scenarios 11, 23 and 29 will also remain undetected.

For the DORMANT operating mode, Table 6.3 shows the sensor readings for the expected behaviour. Scenario 1 is again the only one which indicates the system is working correctly; all other scenarios having the same symptoms contain at least one unrevealed failure. The system could be seemingly working as expected, with all three valves closed and no water in the spill tray, however one of the valves could be closed due to a DORMANT component failure. This will not be identified until either the system is switched into the ACTIVE operating mode, or another failure occurs causing that particular valve to be open. Switching modes would reveal failures in scenarios 13, 17, 37, 41, 49 and 53. This will not reveal any failures in scenario 5, nor a failure causing a problem at V3 in scenarios 17, 41 and 53.

When a control valve system is deemed to be working in a scenario it can only be assumed that those component states which would cause a counter result cannot be valid. For instance, if there is flow at V1 then anything that could cause no flow can be eliminated from the list of possibilities, and if the reading is no flow then anything that could cause immediate flow can be omitted. Any readings in a scenario that are true to the operating mode are indicated using success trees.

Regardless of whether the system is ACTIVE or DORMANT, if the level of water drops to low or even empty, flow is expected into the tank in order to try and replenish that lost. This drop into a discrete level category away from normal will indicate that a failure has occurred in either of the two operating modes. If the water level rises to very high then flow out of the safety valve will be expected. Both of these kinds of flows are ones that are potentially the result of a failure located elsewhere in the system.

If the level of water in the tank rises to high, there should be no flow at V1, regardless of the operating mode. Flow into the system when the level is high can only be the result of a failure at valve V1 causing it to open. If the level in the tank is below normal and there is no flow, then the failure stopping flow can only be something at that particular control valve system in the tank preventing flow in.

6.2.1.6.1 Identification of Potential Scenarios

The flow sensor and level patterns are used to obtain an overall list of potential scenarios that the system could be in. Analysis is also performed looking just at flow sensor patterns as a comparison of results. A technique similar to the decision tree approach used by Novak [18–21] is used to establish a list of scenarios for each set of patterns obtained for the chosen operating mode. A tree of this kind can be used to identify the operating mode, and the flow patterns at the flow sensors, in the overspill tray and the level of water in the tank. The 54 different potential scenarios for the system listed in Table 6.1 have been sorted into tables depending on the patterns and system operating mode as shown in Tables 6.4 and 6.5. An example tree is illustrated in Figure 6.3.

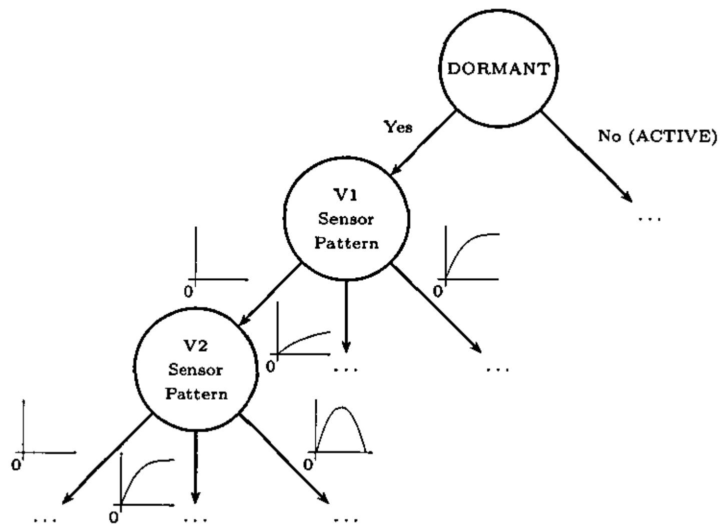


Figure 6.3: An example decision tree for the water tank system

6.2.1.6.2 Identification of Potential Scenario Causes

A method was developed in Chapter 4 that compared the expected system behaviour with that observed in order to reveal any potential faults in the system. This technique is now extended to consider the dynamics of the system. A fault tree has been constructed for each of the deviated sensor readings from the observation points by taking into consideration the pattern history. Symptoms that indicate an observation point to be working are included in the analysis using success trees. Both fault and success trees are non-coherent in structure.

At any given point in time the patterns from the sensors must indicate that the system is potentially in at least one of the 54 possible system scenarios listed in Table 6.1.

TOP Event	Scenario	V1	V2	V3	TANK	Level
ACTIVE1	4, 10, 22, 28					
ACTIVE2	3, 9, 21, 27					
ACTIVE3	2, 6, 8, 12, 20, 24, 26, 30					
ACTIVE4	1, 5, 7, 11, 19, 23, 25, 29					
ACTIVE5	1, 5, 7, 11, 19, 23, 25, 29					
ACTIVE6	16, 34					
ACTIVE7	15, 33					
ACTIVE8	14, 18, 36					
ACTIVE9	14, 18, 32, 36					
ACTIVE10	32					
ACTIVE11	36					
ACTIVE12	36					
ACTIVE13	13, 17, 31, 35					
ACTIVE14	13, 17, 31, 35					
ACTIVE15	31					
ACTIVE16	40, 46					
ACTIVE17	39, 45					
ACTIVE18	38, 42, 44, 48					
ACTIVE19	37, 41, 43, 47					
ACTIVE20	52					
ACTIVE21	51					
ACTIVE22	50, 54					
ACTIVE23	13, 17, 49, 53					
ACTIVE24	49, 53					

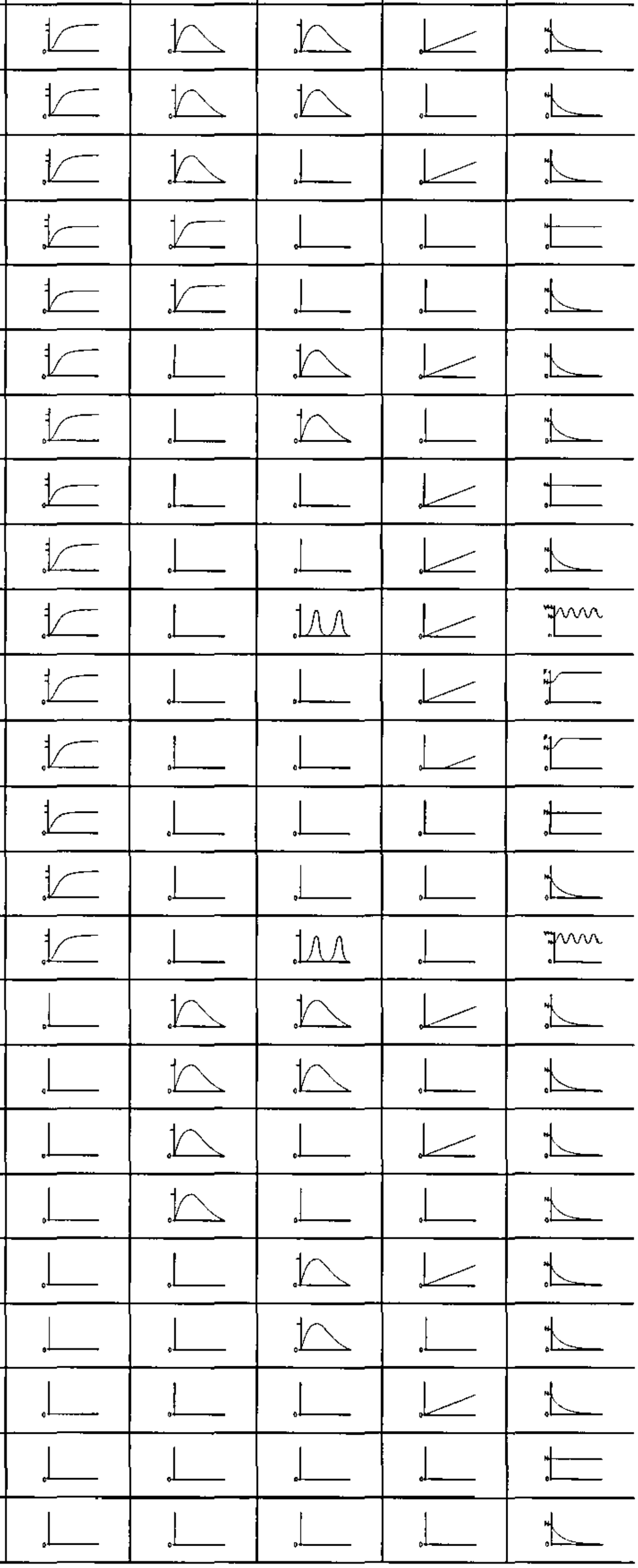


Table 6.4: Possible system readings and their potential scenarios when the system is ACTIVE

TOP Event	Scenario	V1	V2	V3	TANK	Level
DORMANT1	10, 28					
DORMANT2	9, 27					
DORMANT3	8, 12, 26, 30					
DORMANT4	7, 11, 25, 29					
DORMANT5	7, 11, 25, 29					
DORMANT6	4, 16, 22, 34					
DORMANT7	3, 15, 21, 33					
DORMANT8	2, 6, 14, 18					
DORMANT9	2, 6, 14, 18, 24, 32, 36					
DORMANT10	20, 32					
DORMANT11	24, 36					
DORMANT12	23, 24, 36					
DORMANT13	1, 5, 13, 17, 31, 35					
DORMANT14	1, 5, 13, 17, 31, 35					
DORMANT15	19, 31					
DORMANT16	46					
DORMANT17	45					
DORMANT18	44, 48					
DORMANT19	43, 47					
DORMANT20	40, 52					
DORMANT21	39, 51					
DORMANT22	38, 42, 50, 54					
DORMANT23	1, 5, 13, 17, 37, 41, 49, 53					
DORMANT24	37, 41, 49, 53					

Table 6.5: Possible system readings and their potential scenarios when the system is DORMANT

A list of possible scenarios that the system could be in is obtained for each set of sensor patterns, which are shown in Tables 6.4 and 6.5 for the ACTIVE and DORMANT operating modes respectively. Under normal operating conditions the system is expected to exhibit the sensor and level patterns for the ACTIVE4 operating mode as shown in ACTIVE and DORMANT23 for the DORMANT mode.

6.2.1.7 Fault Tree Development

Initial investigations showed that non-coherent fault trees, which are constructed using both working and failed components, provide more reliable results compared to analysis performed using coherent fault trees (see Chapter 4). Therefore only non-coherent fault trees were used when considering the system dynamics.

6.2.1.7.1 Fault Tree Construction

Each fault tree is drawn by taking into consideration the potential causes of failure for each unit in order to restrict these to their own part of the system and inputs and outputs to that section. As an example the fault tree for low flow in section 2 (V2), labelled, 'Section 2 (V2) Low Flow', is described in this Section, the remaining fault trees are given in Appendix C.

Causes of failure observed from the level of water in the tank can also be considered in the analysis. Fault trees are drawn for each of the failure modes. The level pattern for the system can either be within the normal threshold (expected behaviour), decreasing, increasing to very high and then decreasing when the safety valves opens (oscillating), or increasing uncontrollably to full. The tank section contains the level, which is a key factor within in the analysis. The level pattern from the tank takes into consideration all system behaviour as it is affected by all other sections within the system. Therefore the fault trees for the level patterns are as complex as those that were drawn for the original analysis.

Regardless of the level of water in the tank, it has been assumed the system can compensate for flow out through valve V2. Any flow greater than this will result in a decreasing level. A leak in the tank is assumed to have a smaller flow out than that at V2, so a failure causing flow into the system alongside a leak would result in a rising water level. Originally it was assumed that a rupture in the tank would cause no flow out of any of the valves in the system. However it would take time for the tank to empty and this is now identified in the sensor and level patterns.

Low Flow in Section 2 (V2)

The non-coherent fault tree presenting the causes of low flow in section 2 (V2) is shown in Figures 6.4 and 6.5. No flow at V2 can either be because the system is DORMANT and NOT ACTIVE, so a no flow phase is expected at the valve (DORMANT, $\overline{\text{ACTIVE}}$), hence failures indicating no flow at V2 cannot be detected under normal operating conditions, as illustrated in Figure 6.4. The only piece of information known is that the valve has not failed open ($\overline{\text{V2FO}}$), else flow would occur.

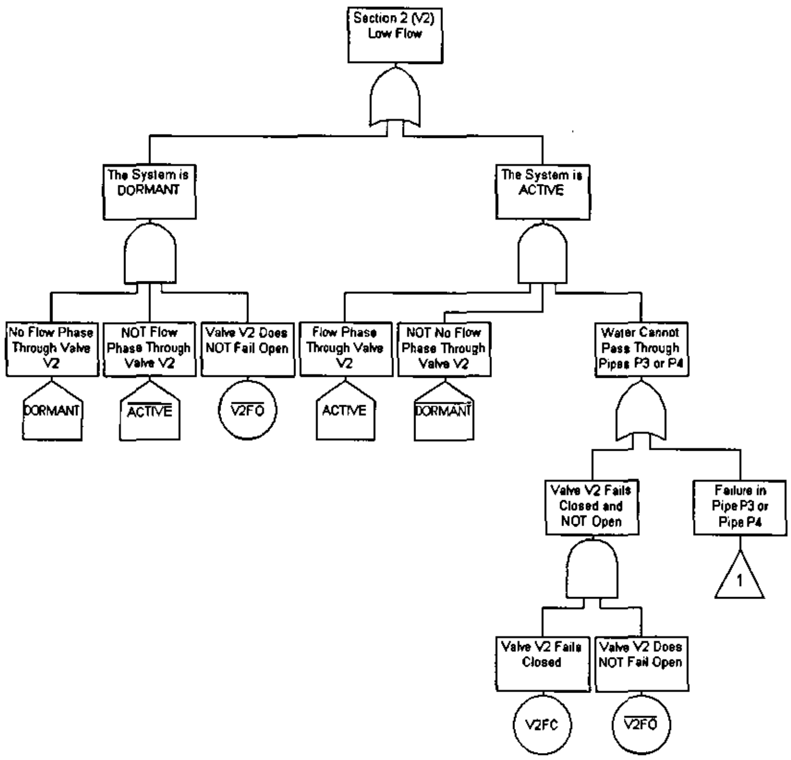


Figure 6.4: Non-coherent fault tree for low flow in section 2 (V2)

If the system is ACTIVE and there is water flow at V2 then there must be a failure preventing flow out (ACTIVE, $\overline{\text{DORMANT}}$), as shown in Figure 6.4. Therefore V2 could be failed closed (V2FC) and not open ($\overline{\text{V2FO}}$) or there could be a failure in pipe P3 or P4. Pipe P3 could be blocked (P3B) and not fractured ($\overline{\text{P3F}}$), or fractured (P3F) and not blocked ($\overline{\text{P3B}}$). Lastly, pipe P4 could be blocked (P4B) and not fractured ($\overline{\text{P4F}}$), as shown in Figure 6.5.

The prime implicants for 'low flow in section 2 (V2)' are listed in Table 6.6. There are 4 in total, all order 2. Table 6.7 lists the potential causes of failure for 'low flow in section 2 (V2)' obtained after performing the coherent approximation, each of which are of single order.

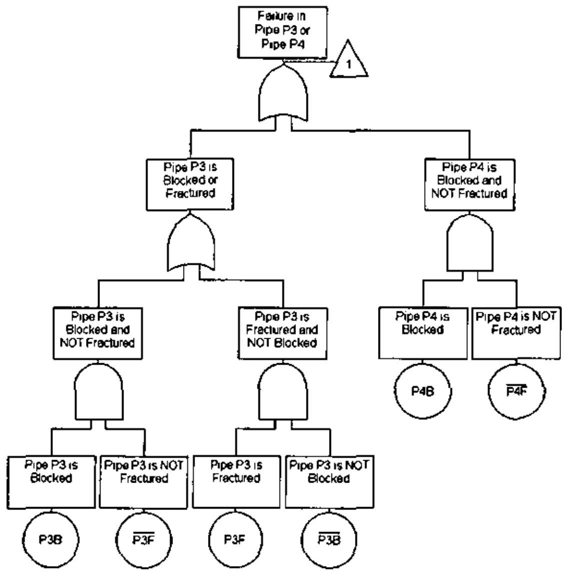


Figure 6.5: Non-coherent fault tree for low flow in section 2 (V2) - transfer 1

Number	Prime Implicants
1)	V2FC.$\overline{\text{V2FO}}$
2)	P3B.$\overline{\text{P3F}}$
3)	P3F.$\overline{\text{P3B}}$
4)	P4B.$\overline{\text{P4F}}$

Table 6.6: Prime implicants for low flow in section 2 (V2)

Number	Potential Causes of Failure
1)	V2FC
2)	P3B
3)	P3F
4)	P4B

Table 6.7: Potential causes of failure for low flow in section 2 (V2) after performing the coherent approximation

6.2.1.7.2 Success Tree Construction

Success trees are comprised of all the component states in the system that cannot have failed for the given sensor reading that is deemed to be working as required. A failure of any of these component states would lead to a contradiction with the top event. Success trees for the water tank system are described in detail in Sections C.2.1 to C.2.6 of Appendix C. There is no success tree for 'water in the overspill tray' as this reading will always result from a failure in either operating modes for all level patterns in the system.

The success trees are only drawn using working states that would have an immediate affect on that particular part of the system and not those where the symptoms that change over time may not be valid for the duration of a level pattern and depend on other sensor readings in the system in order to be true.

Fault trees will therefore need to be built depending on the level pattern of water in the tank and the patterns from the flow readings. These will also be able to identify failures depending on a change in height identified by the level pattern.

Working Low Flow in Section 2 (V2)

Figure 6.6 presents the non-failures of the sensor reading 'Working Low Flow in Section 2 (V2)'. For this sensor reading valve V2 cannot have failed open ($\overline{\text{V2FO}}$) and as the reading is expected the system must be in the DORMANT operating mode, therefore is 'not ACTIVE' ($\overline{\text{ACTIVE}}$).

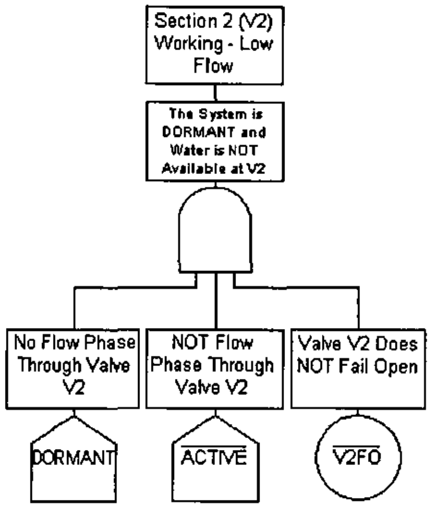


Figure 6.6: Success tree for working low flow in section 2 (V2)

6.2.1.7.3 Possible Component Failures

Table 6.8 lists the possible faults for each of the components in the system and their related code. The failures are the same as in the original system (see Chapter 4), except the level sensor can fail for each height category. As in the steady state conditions, the ACTIVE operating mode indicates that the user has tried to open valve V2 and DORMANT shows the user has attempted to close V2.

Code		Component Failure	Code		Component Failure
P*i*B ($1 \leq i \leq 6$)	-	Pipe P*i* is Blocked	S*i*FL ($1 \leq i \leq 2$)	-	Sensor S*i* Fails Low
P*i*F ($1 \leq i \leq 6$)	-	Pipe P*i* is Fractured	S*i*FE ($1 \leq i \leq 2$)	-	Sensor S*i* Fails Empty
V*i*FC ($1 \leq i \leq 3$)	-	Valve V*i* Fails Closed	C*i*FH ($1 \leq i \leq 2$)	-	Controller C*i* Fails High
V*i*FO ($1 \leq i \leq 3$)	-	Valve V*i* Fails Open	C*i*FL ($1 \leq i \leq 2$)	-	Controller C*i* Fails Low
S*i*FF ($1 \leq i \leq 2$)	-	Sensor S*i* Fails Full	TR	-	Tank Ruptured
S*i*FVH ($1 \leq i \leq 2$)	-	Sensor S*i* Fails Very High	TL	-	Tank Leaks
S*i*FH ($1 \leq i \leq 2$)	-	Sensor S*i* Fails High	NWMS	-	No Water from the Main Supply

Table 6.8: Potential component failures

As in Chapters 4 and 5 the fault and success trees created for each of the sensor readings in the dynamic method were originally drawn by hand and then verified by automating them in FaultTree+. Each of the 54 scenarios listed in Table 6.1 were constructed in FaultTree+ for the ACTIVE and DORMANT operating modes.

6.2.2 Fault Identification - The Application Stage

1. Pattern recognition techniques are used to identify the actual patterns obtained for system sensor readings. These are then compared to those for the expected behaviour. If these patterns match this indicates the system is working as it should be for the given mode or sub-mode. Any pattern that does not match is indicative of a failure of some kind within the system. There may be hidden failures, but these would only become apparent through a change in expected behaviour during system operation, or by switching the operating mode.

2. Sections of the overall system with the potential to have caused the observed symptoms resulting in the incorrect patterns from the key variable transmitters are identified.

3. Each identified section is then investigated in turn and the actual patterns from readings for all the transmitters in that section are checked against those expected. Fault trees are combined for both the deviated and successful patterns for the section

using an AND gate with the status of certain basic events being determined by the transmitter patterns.

4. A list of prime implicants will be obtained from the combined fault tree for each subsystem. A coherent approximation is then made by assuming that all working states are TRUE in order to obtain a list of cut sets.

5. The cut set list obtained is then minimised in order to produce a list of the potential causes of failure for the specified subsystem.

6. If there is more than one potential cause of failure then importance measures can be used to rank the failure modes using their probability of occurrence in order to determine the most likely outcome.

The application stages are now demonstrated for an example from the water tank system.

6.2.2.1 Identification of Actual Patterns

The causes of each scenario is constructed by combining the fault trees for both the deviated and expected readings with an 'AND' gate. The method is now illustrated assuming the system is DORMANT and the patterns obtained are those for DORMANT1 shown in Table 6.9.

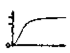
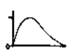
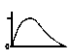
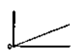
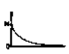
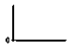
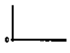
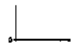
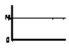
	TOP Event	Potential Scenarios	V1	V2	V3	TANK (Level in TRAY)	Level Pattern
Observed Behaviour	DORMANT1	10, 28					
Behaviour Expected	DORMANT23	1, 5, 13, 17 37, 41, 49, 53					

Table 6.9: DORMANT operating mode with expected and actual sensor readings

Table 6.9 shows the expected flow and level patterns when the system is in the DORMANT operating mode and the corresponding scenarios that could lead to these patterns. The table also lists an example for the actual sensor and level patterns recorded for the system along with their possible scenarios. Each of the 54 scenarios listed in Table 6.1 were constructed in FaultTree+ for the ACTIVE and DORMANT operating modes, so in this particular example scenarios 10 and 28 in the DORMANT mode would be required. The scenarios were then used to develop the overall top events constructed from the system sensor patterns, all of which are shown in Tables 6.4 and 6.5 for the ACTIVE and DORMANT operating modes respectively.

6.2.2.2 Identification of Deviated Key Variables

The results show that in this instance more water is leaving the tank than being replaced, hence the level is decreasing. Flow out at valves V2 and V3 indicate that they are causing high flow when there should be no flow at this point and water in the overspill tray shows that there must be a leak or rupture in the tank. Valve V1 is open because water has been taken out of the system and this always opens in order to replenish any water lost. Another possibility is that a failure could have occurred causing V1 to be open. Hence the two possible scenarios for the system with the given sensor and level patterns are 10 and 28.

6.2.2.3 TOP Event Structure Construction

Figures 6.7 and 6.8 show the structure for scenarios 10 and 28 respectively together with the corresponding level pattern. Not all level patterns are valid for each set of flow sensor scenarios.

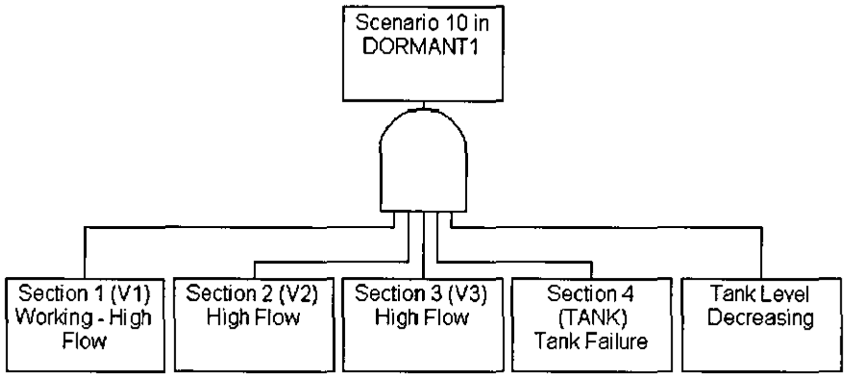


Figure 6.7: Structure for scenario 10 in the DORMANT operating mode

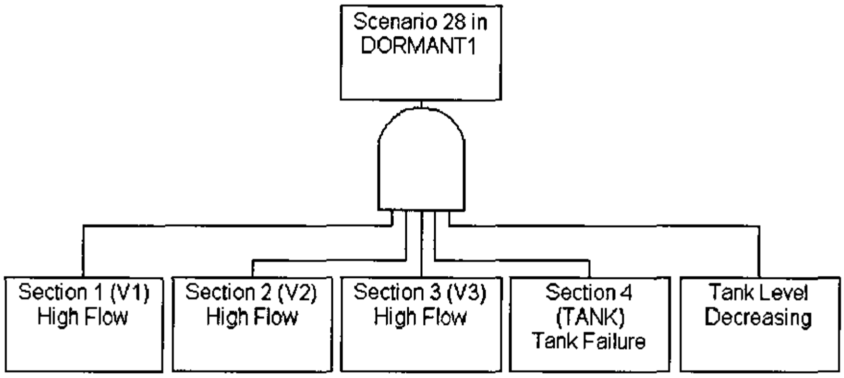


Figure 6.8: Structure for scenario 28 in the DORMANT operating mode

Both deviated and working readings are included in the diagrams. The scenarios for each set of patterns are then combined using an 'OR' gate to form the overall TOP event for the sensor and level patterns, as shown in Figure 6.9.

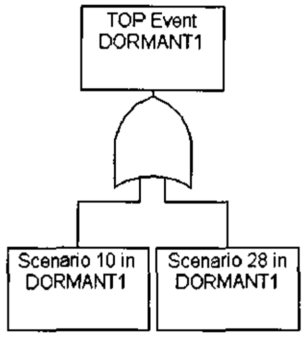


Figure 6.9: TOP event structure for DORMANT1

6.2.2.4 Prime Implicants

A qualitative analysis of the fault tree in Figure 6.9 will produce prime implicants indicating the potential causes of the TOP event DORMANT1. An example of a prime implicant obtained is:

$$\text{V2FO.V3FO.TL.}\overline{\text{V1FC}}.\overline{\text{C1FH}}.\overline{\text{S1FH}}.\overline{\text{S1FVH}}.\overline{\text{S1FF}}.\overline{\text{P1B}}.\overline{\text{P1F}}.\overline{\text{P2B}}.\overline{\text{NWMS}}.\overline{\text{V2FC}}.\overline{\text{P3B}}.\overline{\text{P3F}}.\overline{\text{P4B}}.\overline{\text{V3FC}}.\overline{\text{P5B}}.\overline{\text{P5F}}.\overline{\text{P6B}}.\overline{\text{TR}}.$$

This prime implicant is of order 21. In total 10 prime implicants are obtained, 2 of order 21, 2 of order 22 and 6 order 26.

6.2.2.5 Potential Causes of System Failure

Performing the coherent approximation removes any working component state from the prime implicants and yields a list of the potential causes of failure. These are shown for the given example in Table 6.10.

Number	Potential Causes
1)	V2FO.V3FO.TL
2)	V2FO.V3FO.TR
3)	V2FO.C2FH.TL
4)	V2FO.C2FH.TR
5)	V2FO.S2FH.TL

Number	Potential Causes
6)	V2FO.S2FH.TR
7)	V2FO.S2FVH.TL
8)	V2FO.S2FVH.TR
9)	V2FO.S2FF.TL
10)	V2FO.S2FF.TR

Table 6.10: Potential causes of failure for the TOP event DORMANT1

All 10 of the potential causes of failure obtained for DORMANT1 are valid and the method has correctly identified all possibilities. Analysis has also been performed using just the flow sensor readings, the results obtained for this particular example were the same as for using flow and level readings, as shown in Table 6.10. Using just the flow sensor readings would have therefore reduced the complexity of the analysis and obtained the same outcome in this instance. In both cases importance measures would be used to identify the most likely potential cause of failure as there is more than one possibility obtained from the analysis as the list cannot be reduced down any further.

6.2.2.6 Ranking of Failure Modes

Table 6.11 shows the unavailability of each component, assuming that the deviation occurred at t = 600s.

Component Failure	Conditional Failure Rate	Unavailability Failure Rate	Importance
V2FO	1.5×10^{-7}	8.9995949×10^{-5}	1.000
V3FO	1.5×10^{-6}	8.9959512×10^{-4}	0.0867873
S2FH-S2FF	2.8×10^{-6}	1.678589587×10^{-3}	0.485819412
C2FH	7.4×10^{-6}	4.430151777×10^{-3}	0.427393286
TL	1.0×10^{-8}	5.999981×10^{-6}	0.0038434507
TR	2.6×10^{-6}	1.558783831×10^{-3}	0.996165616

Table 6.11: Component failure rate and unavailability

Q_{SYS} is determined using the Rare Event Approximation and for this example was found to be $Q_{SYS} = 1.45971626\times10^{-9}$. The Fussell-Vesely measure of component importance (see Section 3.7.2.2) has been used to indicate which components are most likely to contribute to the failure of a system through identifying the occurrence of a minimal cut set containing a given component. The importance for each component is shown in Table 6.11. The results indicate that valve V2 has failed open, it is likely that the tank has ruptured and also sensor S2 has failed causing flow out at valve V3.

Using the Fussell-Vesely measure of minimal cut set importance (see Section 3.7.2.1) has shown that there are 3 most likely causes of failure: V2FO.S2FH.TR, V2FO.S2FVH.TR, V2FO.S2FF.TR. There are three results due to the component failure rate of sensor S2 being the same for each of the three given failure possibilities. In two of these valve V2 has failed open causing a failure in section 2 and the tank has ruptured resulting in a catastrophic leak in the tank.

6.3 Results

Results obtained for the water tank system are shown in Tables 6.12 and 6.13 for the ACTIVE and DORMANT operating modes respectively. Effectiveness Index I_{E_k} (where k denotes ACTIVE or DORMANT operating modes), shown in Section 4.5.2.1 is calculated for the TOP event structures. In this case N is the number of level patterns investigated, n_i is the number of potential causes of failure identified by the method for TOP event T, nc_i is the number of these that are correct causes of the observed symptom behaviour for T and na_i is the actual number of correct possible causes for T.

TOP Event	Scenarios Used to Build TOP Event	Results With Level		Results Without Level		Number of Actual Possibilities
		n_i	nc_i	n_i	nc_i	
ACTIVE1	4, 10, 22, 28	10	10	10	10	10
ACTIVE2	3, 9, 21, 27	5	5	5	5	5
ACTIVE3	2, 6, 8, 12, 20, 24, 26, 30	2	2	2	2	2
ACTIVE4	1, 5, 7, 11, 19, 23, 25, 29	-	-	-	-	-
ACTIVE5	1, 5, 7, 11, 19, 23, 25, 29	1	1	0	0	1
ACTIVE6	16, 34	40	40	40	40	40
ACTIVE7	15, 33	20	20	20	20	20
ACTIVE8	14, 18, 36	4	3	8	3	3
ACTIVE9	14, 18, 32, 36	8	8	8	8	8
ACTIVE10	32	12	12	32	12	12
ACTIVE11	36	72	72	224	72	72
ACTIVE12	36	72	72	224	72	72
ACTIVE13	13, 17, 31, 35	4	1	4	1	1
ACTIVE14	13, 17, 31, 35	4	4	4	4	4
ACTIVE15	31	12	12	16	12	12
ACTIVE16	40, 46	90	90	90	90	90
ACTIVE17	39, 45	45	45	45	45	45
ACTIVE18	38, 42, 44, 48	18	18	18	18	18
ACTIVE19	37, 41, 43, 47	9	9	9	9	9
ACTIVE20	52	360	360	360	360	360
ACTIVE21	51	180	180	180	180	180
ACTIVE22	50, 54	72	72	72	72	72
ACTIVE23	13, 17, 49, 53	4	3	4	3	3
ACTIVE24	49, 53	36	36	36	36	36
Effectiveness Index $I_{E_{ACTIVE}}$		0.946		0.788		(to 3 decimal places)

Table 6.12: Results and effectiveness index obtained when the system is in the ACTIVE operating mode

The range of the effectiveness index is from 0 to 1, with 0 indicating the method is not effective and 1 indicating that it is completely effective. An index less than 1 is expected as some failures in the system may be unreachable. Results from the analysis have been obtained for with and without the tank level patterns.

TOP Event	Scenarios Used to Build TOP Event	Results With Level		Results Without Level		Number of Actual Possibilities
		n_i	nc_i	n_i	nc_i	
DORMANT1	10, 28	10	10	10	10	10
DORMANT2	9, 27	5	5	5	5	5
DORMANT3	8, 12, 26, 30	2	2	2	2	2
DORMANT4	7, 11, 25, 29	1	1	1	1	1
DORMANT5	7, 11, 25, 29	1	1	1	0	1
DORMANT6	4, 16, 22, 34	10	10	10	10	10
DORMANT7	3, 15, 21, 33	5	5	5	5	5
DORMANT8	2, 6, 14, 18	1	1	2	1	1
DORMANT9	2, 6, 14, 18, 24, 32, 36	3	3	2	1	3
DORMANT10	20, 32	4	4	8	4	4
DORMANT11	24, 36	24	24	56	24	24
DORMANT12	24, 36	24	24	56	24	24
DORMANT13	1, 5, 13, 17, 31, 35	0	0	0	0	1
DORMANT14	1, 5, 13, 17, 31, 35	1	1	0	0	1
DORMANT15	19, 31	4	4	4	4	4
DORMANT16	46	90	90	90	90	90
DORMANT17	45	45	45	45	45	45
DORMANT18	44, 48	18	18	18	18	18
DORMANT19	43, 47	9	9	9	9	9
DORMANT20	40, 52	90	90	90	90	90
DORMANT21	39, 51	45	45	45	45	45
DORMANT22	38, 50, 54	18	18	18	18	18
DORMANT23	1, 5, 13, 17, 37, 41, 49, 53	-	-	-	-	-
DORMANT24	37, 41, 49, 53	18	18	18	18	18
Effectiveness Index $I_{E_{\text{DORMANT}}}$		0.942		0.740		(to 3 decimal places)

Table 6.13: Results and effectiveness index obtained when the system is in the DORMANT operating mode

In the majority of cases the method has correctly identified the possible number of potential causes of failure for both the ACTIVE and DORMANT operating modes when using tank level sensor patterns. This is reflected in the Effectiveness Index for each mode, which is $I_{E_{\text{ACTIVE}}} = 0.945652173$ and $I_{E_{\text{DORMANT}}} = 0.942028985$ for ACTIVE and DORMANT respectively. These scores give an average of $I_E = 0.944$ (to 3 decimal places), and indicates that although the method is not perfect (the effectiveness index would be $I_E = 1.000$) it is very effective at obtaining the potential causes of system failure for the water tank.

In the ACTIVE operating mode there are three TOP events that do not yield the correct potential failure causes when the tank level patterns are included in the analysis, these being ACTIVE8, ACTIVE13 and ACTIVE23. ACTIVE8 indicates that there is flow into the system through V1, no flow out at V2 and V3, and water in the overspill tray.

As there is a normal tank level pattern water in the spill tray can only be caused by a leak in the tank (TL) because a rupture would result in a decreasing level, and water overspilling the sides would show that the tank was full. If the tank is leaking then no flow out of V2 cannot be caused by a fracture in pipe P3 as this together with the tank leaking would cause the water level to decrease. Therefore either V2 has failed closed (V2FC), or pipes P3 or P4 are blocked (P3B, P4B). The potential causes of failure obtained are TL.V2FC, TL.P3B or TL.P4B. The method also indicates that TL.P3F is a possibility, which is an invalid result as they should only occur together for a decreasing tank level. Similarly for ACTIVE13 the potential causes of failure obtained are pipe P3 is fractured (P3F), V2FC, P3B or P4B. With a normal level and flow in through V1 only P3F is a valid result. For ACTIVE23 there is no water going out of the system or coming into the system through V1 indicating that either pipe P3 or P4 is blocked or V2 has failed closed. When the level is normal it is difficult to identify if pipe P3 is fractured because the level fluctuates within the required threshold. DORMANT13 is the only TOP event for the DORMANT operating mode that has failed to identify the correct potential causes of failure. This TOP event fails to indicate that pipe P3 could also be fractured along with the tank leaking to create a third potential cause of failure for this scenario.

The use of fault trees that are restricted to the control systems on each stream has reduced the complexity of the approach. The dynamic method now needs to be scaled up by carrying out further investigations on larger systems in order to test its feasibility.

Original analysis was carried out in steady state, without including the level of water in the tank. The extended analysis has also been carried out without the tank level patterns, these results are shown in Tables 6.12 and 6.13 for the ACTIVE and DORMANT operating modes respectively in the column headed 'Results Without Level'. The method is less complex compared with that which includes the tank level patterns

The results show that the method is less effective at obtaining the exact list of potential failure causes for each TOP event compared to those including the tank level. This is reflected in the Effectiveness Index, which is, $I_{E_{\text{ACTIVE}}} = 0.788819875$ and $I_{E_{\text{DORMANT}}} = 0.740165631$ for the ACTIVE and DORMANT operating modes respectively. This gives an average of $I_E = 0.764$ (to 3 decimal places). In some instances the method has obtained potential failure causes for a number of TOP events that are known to be incorrect, along with those which could cause the TOP event to occur. Incorrect readings have occurred in ACTIVE5, ACTIVE8, ACTIVE13 and ACTIVE23, along with DORMANT5, DORMANT8 to DORMANT14 and DORMANT24. This strengthens the need to include the tank level within the analysis.

The method is not able to identify any hidden failures of components that have the same symptoms as when they are working as required. For instance if the system is ACTIVE and the level patterns are as shown in Table 6.2 then it is assumed that the system is working normally. However, there may be a failure at valve V3 causing it to stay closed. This will not be identified until this part of the system is used. In DORMANT3 shown in Table 6.13 the potential causes of failure is either V2FO.TL or V2FO.TR. In this case though there could be flow out at V3 through a fracture in pipe P5. This could be identified by using the exact flow information in the analysis rather than just flow patterns.

Valve V2 failing open or closed can be identified by switching the operating mode of the tank. If the valve is allowing water out of the system when ACTIVE, switching the mode to DORMANT should close the valve as the system moves into a no flow phase at V2. If it remains open then V2 has failed open. Similarly if the system is DORMANT V2 should be closed and if the valve remains closed after moving into the ACTIVE mode then it has failed in that way.

6.4 Consideration of Dynamics Within the Fault Detection Demonstration

A detailed discussion of the results obtained for the four fault tree based schemes were described in Chapter 4. Scheme 4 containing an immediate consistency check was concluded to be the most accurate for obtaining the potential causes of failure for given system behaviour. It was highlighted that dynamics would need to be considered in order to improve the overall accuracy. Transient effects were therefore accounted for in Chapter 6 through the use of a simple pattern recognition technique. The fault detection demonstration has been extended to show this.

The simulation models the behaviour of the water tank system as previously described for the four schemes. The pattern of the results at each of the sensors in the system is now obtained from the simulation and compared against the expected behaviour in the given operating mode. There are 24 possible flow patterns for each of the modes, as shown in Tables 6.2 and 6.3 for ACTIVE and DORMANT respectively. The patterns from the sensors indicate that the system is in at least one of the 54 possible system scenarios listed in Table 6.1. A list of possible scenarios is therefore obtained for the system from the given set of sensor patterns. The program takes the identified pattern from the given set of results and compares this with the expected patterns in order to determine the possible system scenarios. The sensor readings for each scenario are combined with an AND gate and the scenarios for each set of flow patterns are combined with an OR gate to give the overall TOP event structure, as shown in general in Figure 6.10.

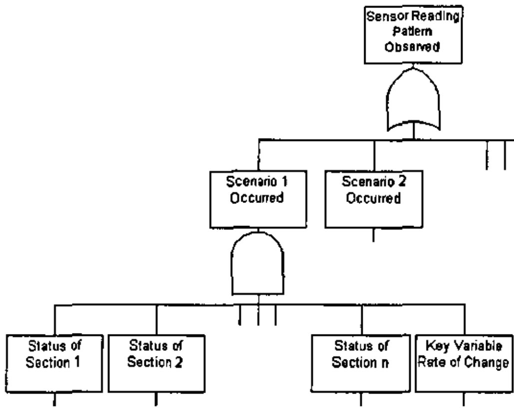


Figure 6.10: General TOP event structure

The fault induced into the system was valve V1 fails closed. Analysis is performed as before, giving a list of potential causes of failure for the given flow patterns.

Dynamic Example

The expected flow and level patterns when the system is in the ACTIVE operating mode and the corresponding scenarios that could lead to these patterns are shown in Table 6.14. An example for the actual sensor and level patterns recorded for the system along with their possible scenarios is also shown.

	TOP Event	Potential Scenarios	V1	V2	V3	TANK (Level in TRAY)	Level Pattern
Observed Behaviour	ACTIVE19	37, 41, 43, 47					
Behaviour Expected	ACTIVE4	1, 5, 7, 11 19, 23, 25, 29					

Table 6.14: ACTIVE operating mode with expected and actual sensor readings

The example indicates that water is leaving the tank, but it is not being replaced by flow through valve V1, leading to a decrease in the water tank level. The possible scenarios for the system in this case are 1, 5, 7, 11, 19, 23, 25 or 29. Performing analysis results in potential causes of failure for the system, as shown in Table 6.15.

Number	Potential Causes
1)	V1FC
2)	C1FH
3)	S1FH
4)	S1FVH
5)	S1FF

Number	Potential Causes
6)	P1B
7)	P1F
8)	P2B
9)	NWMS

Table 6.15: Potential causes of failure for the TOP event DORMANT1

Measures of importance were used as in the steady-state examples. Valve V1 failing closed was found to be the most likely cause of failure in this particular example.

6.5 Summary

- Consideration of the system dynamics has improved the method and obtained more accurate results. In the majority of cases the method has correctly identified the possible number of potential causes of failure for both the ACTIVE and DORMANT operating modes, which is reflected in the Effectiveness Index.
- The use of fault trees that are restricted to the control systems on each stream has reduced the complexity of the approach and should enable the method to be scaled up for use on larger systems. Further investigation of this will follow using the BAE Systems fuel rig.
- The analysis needs to include the tank level patterns in order to obtain accurate results about the system behaviour. The level of water in the tank is the key variable in the system. A deviation with this reading in the system will affect the overall ability of the system to maintain the amount of water between the chosen limits.
- The method is not able to identify any hidden failures of components that have the same symptoms as when they are working as required. This is a restriction in the analysis that cannot be resolved.
- The program has been extended to demonstrate the method when considering transient effects.

Chapter 7

Application of the Dynamic Method to the Fuel Rig

7.1 Introduction

This chapter describes the extension of the dynamic method by applying it to a model based on a fuel rig from BAE Systems. The fuel rig system is a model that symbolises the functions of a real aircraft system, using water to simulate fuel flow. Fluid is fed from a wing and main tank into a collector tank, which then outputs to the engine. This features redundancy and is a larger system than the previously considered simple water tank level control system.

7.2 Dynamic Fault Detection and Identification Process

The dynamic fault detection and identification process is categorised into two stages, these being 'modelling and preparation' and 'application' as shown previously in Chapter 6. These are now modified in light of having applied the method to a system of increased complexity and featuring redundancy. The modelling and preparation stage is the part of the analysis in which all available information about the system is collected. This information is then used in the application stage in order to ascertain the cause of failure from symptoms exhibited on the system. The updated stages are described in more detail in Sections 7.2.1 and 7.2.2 respectively for a general system.

7.2.1 Modelling and Preparation Stage

1. The system is first divided into sections or subsystems. These are parts that can change the system process variables by either normal control action or through the occurrence of a component failure. Subsystems should provide a single function in the system, providing inputs to or being outputs from other sections within the system. The overall system must have a key function and one of the sections must be associated with this key process variable so to determine the outcome of the system. Sections will show a natural decomposition or breakdown of the whole system. The way to identify these would be to look at the input/outputs and identify the key ones of these, which will then indicate the main areas in a system.

2. The subsystem process variables that are to be measured, such as flow, temperature, pressure or level are identified. Sensors are then incorporated into the system to monitor these variables if not already present for control purposes.

3. Key locations of the measured process variables in each section are identified. These locations will be those points where a change in normal control action will initially become apparent. This output of information can then be used to alter the status of other parts of the system if required. The locations of these will be determined by the system sectioning carried out in Stage 1.

4. All the possible modes of system operation at any point in time are listed. Modes of operation may also be divided further into appropriate 'sub-modes' in the event that its complexity is too difficult to deal with on its own. The sub-modes will be determined by the size of the system and how the sectioning has been carried out. Assumptions to be made that can affect the operation of the system are identified.

5. All system scenarios are developed. The scenarios consider all possible deviations in the process variables on each section. They may be failed high, partial, low or working as normal. On sections where there is a control system, the deviations may be due to control system failures. Deviations can also occur due to the failure of passive components such as pipes or wires. Some sections may contain only passive elements of the system in which case changes in the related process variable will only happen when a failure mode occurs or through changes in section inputs and outputs.

6. For each of the system operating modes identified, a set of potential patterns from the readings obtained for the key measured variables are developed. Any potential

behaviour for individual sub-modes if used in the analysis of a specified mode is also included.

7. For each section the potential pattern behaviour for any other transmitter readings that can be taken are identified. Again, if sub-modes are used then identify the possible behaviour for each of these. Only the shape of the sensor reading pattern is required.

8. Fault trees for causes of the process variable deviation at each of the sensor locations used to define the scenarios are drawn. Each fault tree is developed down to the component failures in the system. Fault trees may be drawn for absolute values or rates of change, depending on what information is considered useful for the particular system. For any normal system behaviour causes of sensor readings are developed using success trees, which describe all the components in the system that must be working correctly in order for that outcome to occur.

7.2.2 Application Stage

1. Pattern recognition techniques are used to identify the actual patterns obtained for system sensor readings. These are then compared to those for the expected behaviour. If these patterns match this indicates the system is working as it should be for the given mode or sub-mode. Any pattern that does not match is indicative of a failure of some kind within the system. There may be hidden failures, but these would only become apparent through moving into a different sub-mode during system operation, or by switching the operating mode.

2. Sections of the overall system with the potential to have caused the observed symptoms resulting in the incorrect patterns from the key variable transmitters are identified.

3. Each identified section is then investigated in turn and the actual patterns from readings for all the transmitters in that section are checked against those expected. Fault trees are combined for both the deviated and successful patterns for the section using an AND gate with the status of certain basic events being determined by the transmitter patterns. In the case of the fuel rig system each section is representative of a tank subsystem.

4. A list of prime implicants will be obtained from the combined fault tree for each subsystem. A coherent approximation is then made by assuming that all working states are TRUE in order to obtain a list of cut sets.

5. The cut set list obtained is then minimised in order to produce a list of the potential causes of failure for the specified subsystem.

6. If there is more than one potential cause of failure then importance measures can be used to rank the failure modes using their probability of occurrence in order to determine the most likely outcome.

The process described is now demonstrated by applying it to a representation of an aircraft fuel supply system. This system exists as an experimental fuel rig, located at BAE Systems.

7.3 The Fuel Rig System

The aim of any aircraft fuel system is to provide an adequate supply of clean fuel at an appropriate pressure level throughout the flight phase to all the engines. The fuel rig system, illustrated in Figure 7.1, is a model representing a real aircraft fuel system that uses water to simulate the fuel flow. The rig consists of three tanks; main, wing and collector in which water is distributed to the engine feed.

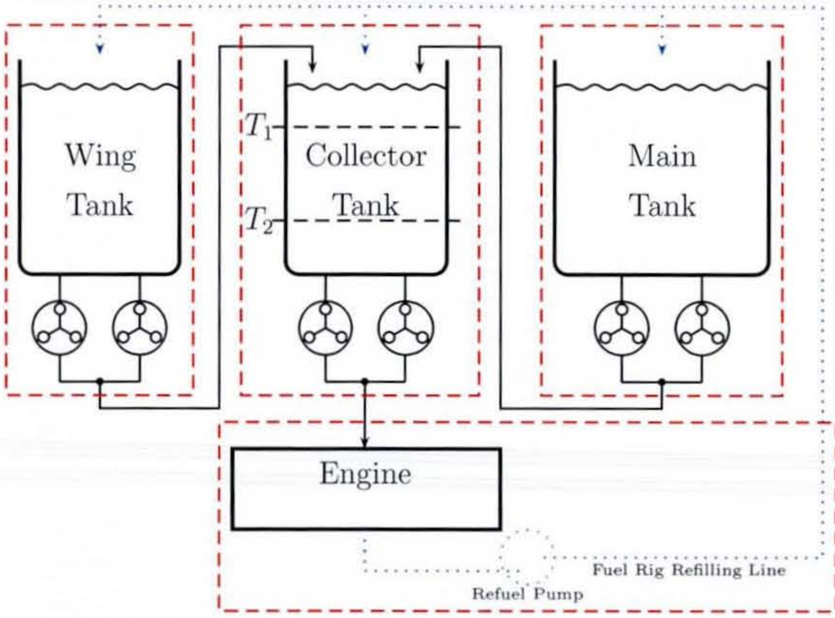


Figure 7.1: The fuel rig system

A photo of the actual fuel rig system is shown in Figure 7.2, courtesy of BAE Systems.

Figure 7.2: Photo of the fuel rig system

7.3.1 System Component Description

Each tank has two pump trains, each containing a peristaltic pump (PP$****$), pressure sprung relief valve (PSV$****$), powered isolation valve (IVP$****$) controlled by a controller (CT$****$), back pressure valve (BP$****$) and connecting pipe work (P$****$) [1]. These are shown in Figure 7.3 for the main tank. In total the tank unit contains seven valves; 3 powered isolation valves, 2 pressure relief valves and 2 back pressure valves. Each powered isolation valve has an associated controller. In total each unit consists of 23 sections of pipe.

The two fuel line streams out of each tank are labelled 'Line L1' and 'Line L2' in this diagram. These join up to become the main outflow line of the tank. Either of the two lines can be used when fuel is required, but fuel is only drawn out of one line from each tank at any point in time, the second is left in a standby mode and used in the event of a failure in the first, thus providing the system with redundancy.

When the engine is switched on all peristaltic pumps turn on, including those on lines that are on standby. When fuel is not required from a line the powered isolation valve remains closed, and the water is re-circulated back into the tank via the recycle line, as shown in

[1] '$****$' represents the component code.

more detail for a single tank section (this being for the main tank (TK∗∗∗∗)) in Figure 7.3. The fluid flow along each recycle line is regulated by a pressure relief valve.

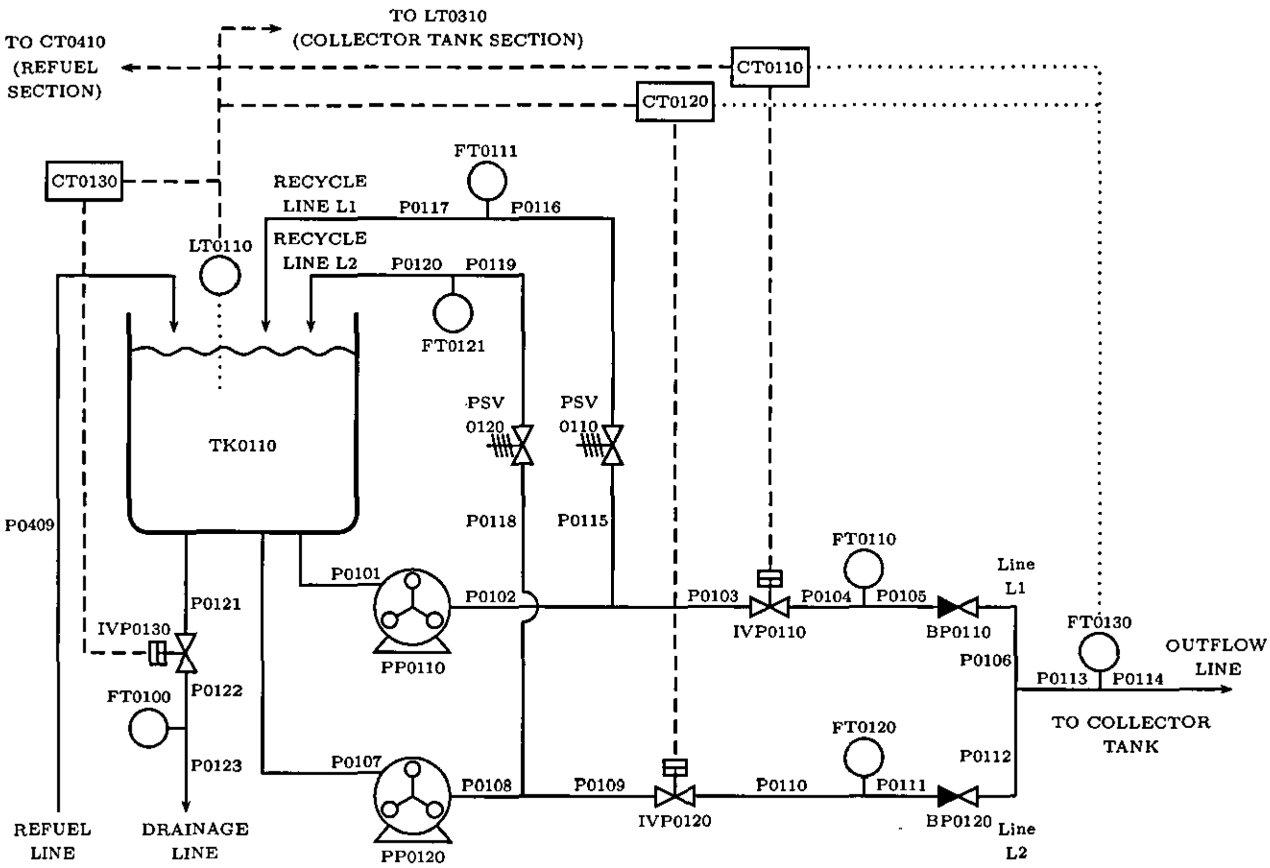


Figure 7.3: Main tank from the fuel rig system

Water is fed only to the engine from the collector tank (Figure 7.1). Both main and wing tanks are used to feed the collector tank when the level of water drops below a designated threshold. The wing tank, which simulates the auxiliary fuel storage in the system, is used for replenishing the collector tank when the level of water drops to or below threshold T_1. Once the supply of water from the wing tank has been used and/or the level in the collector tank drops to or below threshold T_2 fluid will then be fed from the main tank, which simulates the main fuel storage in an aircraft system. It is assumed that under normal operating conditions water is pumped into the collector tank at the same rate as it is pumped out into the engine. Therefore the water level in the collector tank will increase only as a result of a failure causing flow into the tank from another part of the system. The engine in the fuel rig system is represented by a large tank located at the base of the rig.

The main, wing and collector tanks each have a powered isolation valve for drainage controlled by a controller, which may be used to represent the dumping of fuel from an aircraft. In this case the main and wing fuel lines are shut down and both these tanks are drained of water to pump shut off. The collector tank is also drained to a low level, leaving enough fuel for landing. The water from all the tanks is drained into the engine tank in the rig so that it can be redistributed back into the system. Each of these tank units are comprised of six flow transmitters (FT$****$); one after each of the powered isolation valves on the main lines out of the tank, one where the two main lines join, one on each of the over flow lines and finally one on the drainage line to detect when the system is being drained. Finally a level sensor is located inside each tank (LT$****$).

The wing and collector tanks in the fuel rig system contain the same type of components as those described for the main tank, the only disparity being that the numbers in the codes for these tanks start '02' and '03'respectively (for the main tank they begin with '01').

7.3.2 Level Transmitter Thresholds

The readings from the level transmitters in the main, wing and collector tanks are: 'empty' (E), 'pump shut off' (PSO), 'low' (L), 'adequate section' (AS), 'required level' (RL), 'high' (H) and 'full' (F) as shown in Figure 7.4. When the system is dumping fuel the main and wing tanks are both drained to PSO, and the collector tank is drained to L so that only a minimal amount of fuel is left for the simulation of an aircraft landing.

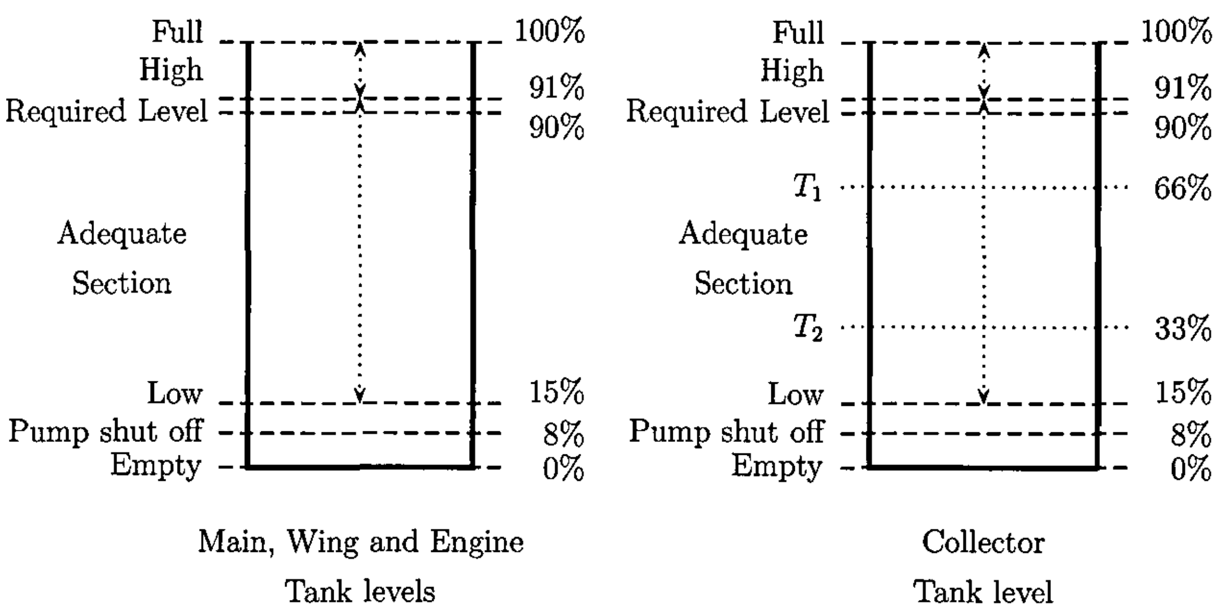


Figure 7.4: Tank levels for the fuel rig system

In addition to these the adequate section in the collector tank is divided up depending on the thresholds T_1 and T_2. If the level in the collector tank is above threshold T_1 then there is no flow into the tank from the main or wing tanks. Once the level drops below this, if there is water above pump shut off in the wing tank then the powered isolation valve on either of the stream lines is opened (as pre-determined before analysis commences) to allow fluid flow into the collector tank in order to keep the tank replenished with a stock of fuel. Once the level in the collector tank drops to threshold T_2 the powered isolation valve on either of the stream lines in the main tank section opens to allow fluid from the main tank to refill the collector tank. The pumps will automatically switch off as soon as the level in that specific tank drops to PSO to prevent them from becoming damaged, which leads to a breakdown of part or even the whole system. In the event that fluid flow does not commence out of a tank, the controller on the redundant line will then be expected to open the respective powered isolation valve. This will either allow the system to function as required or in the event of a failure on this line cause a break down in the whole tank section.

7.4 System Stages

7.4.1 System Modelling and Preparation Stage

The sub-stages 1 to 7 described in Section 7.2.1 are now described for the fuel rig system.

7.4.1.1 System Division

The fuel rig has a total of 26 flow and 4 level transmitters. It is too complex to account for all this system knowledge at the same time. The size of the problem therefore needs to be reduced and this is carried out by modularising the analysis. This involves identifying the area or areas in which a deviation has occurred and then focusing in on each one individually to determine the possible causes of failure for that particular section. The fuel rig is divided into 4 'subsystems' as shown by the dashed lines in Figure 7.1. Three of the subsystems contain the main, wing and collector tanks, and the fourth contains the refuelling part. These sections have been identified from a schematic of the whole fuel rig.

7.4.1.2 Identification of System Sensors

Information regarding the status of the system is obtained using two different types of transmitter or 'observable points'; these being able to measure either flow or level. The main, wing and collector tank subsystems each possess a level transmitter within the tank itself, which is labelled LT0110 in Figure 7.3 for the main tank. There are also six flow transmitters; one after each of the powered isolation valves on L1 and L2 out of the tank (FT0110, FT0120), one where these lines join up on the main outflow line (FT0130), one on each of the recycle lines (FT0111, FT0121) and finally one on the drainage line (FT0100). Therefore these sensors are all monitored in order to highlight the occurrence of any deviations.

7.4.1.3 Identification of Key Process Variables

The key process variables in the overall system are the level in the collector tank (LT0310) and the flow on the main outflow line of each of the three tanks (FT0130, FT0230 and FT0330). The level in both the main and wing tanks (LT0110 and LT0210) are also important factors to the system functionality as these could lead to the identification of a problem in an individual tank section.

7.4.1.4 Modes of System Operation and System Assumptions

7.4.1.4.1 Modes of System Operation

The system has two main modes of operation; these being 'ACTIVE' when all pumps are on and fluid is pumped from the collector tank to the engine, or 'DORMANT' when all the pumps are shut down and there is no fluid transfer. In the ACTIVE operating mode as the transfer of water between the collector tank and the engine takes place the level of water in the collector tank decreases. This is replaced by water being transferred, initially from the wing and then later on from the main tank.

7.4.1.4.2 System Operating Assumptions

A number of assumptions have been made regarding the operation of the fuel rig system:

- A blockage in a pipe or valve will prevent any flow of fluid through this component.

Similarly a partial blockage will reduce the amount of fluid flow in a pipe or through a valve, but not stop it completely.

- A fracture in a pipe will result in fluid leaving the system at this point, preventing any flow of fluid further into the system. A leak in a pipe or valve will cause partial flow and result in some loss of fluid from the system. All fluid losses cannot be replenished.
- A rupture in one of the tanks results in a loss of fluid out of the system that cannot be replenished. A rupture in the collector tank will lose fluid faster than it can be refilled from its supply.
- For simplicity, the system will always start off with the required level of fuel in the main, wing and collector tanks.
- The system sensors are assumed to be reliable in this case.

A tank deviation will result in failure to indicate the required fluid level in that particular tank. In the water tank example the system had a tray beneath the tank to catch any fluid lost through a leak, rupture or from overfilling. This was used to distinguish whether the tank was working or had failed. The tanks in this example do not have trays, therefore the possibility of a tank failure cannot be ruled out from the possible causes of system failure.

7.4.1.5 System Scenarios and Patterns for the Key Process Variables

The sensors for the key process variables are used to generate a set of scenarios that the system could potentially be in. These are defined firstly for the key process variables in the system and then for the other sensors within a section.

7.4.1.5.1 System Scenarios

The flow from each tank section can be indicated as functioning normally (WK), failed in a mode that causes high flow (HF) (eg: valve open), failed resulting in partial flow (PF) (eg: valve failed partially open) or failed in a mode that causes low flow (LF) (eg: valve closed). If a section of the system is working this indicates that fluid is being provided from that part as and when required in response to the system state and operating mode. There are 64 different potential scenarios that can occur in the system as shown in Table 7.1.

Scenario	MAIN SECTION	WING SECTION	COLLECTOR SECTION	Scenario	MAIN SECTION	WING SECTION	COLLECTOR SECTION
1	WK	WK	WK	33	PF	WK	WK
2	WK	WK	HF	34	PF	WK	HF
3	WK	WK	PF	35	PF	WK	PF
4	WK	WK	LF	36	PF	WK	LF
5	WK	HF	WK	37	PF	HF	WK
6	WK	HF	HF	38	PF	HF	HF
7	WK	HF	PF	39	PF	HF	PF
8	WK	HF	LF	40	PF	HF	LF
9	WK	PF	WK	41	PF	PF	WK
10	WK	PF	HF	42	PF	PF	HF
11	WK	PF	PF	43	PF	PF	PF
12	WK	PF	LF	44	PF	PF	LF
13	WK	LF	WK	45	PF	LF	WK
14	WK	LF	HF	46	PF	LF	HF
15	WK	LF	PF	47	PF	LF	PF
16	WK	LF	LF	48	PF	LF	LF
17	HF	WK	WK	49	LF	WK	WK
18	HF	WK	HF	50	LF	WK	HF
19	HF	WK	PF	51	LF	WK	PF
20	HF	WK	LF	52	LF	WK	LF
21	HF	HF	WK	53	LF	HF	WK
22	HF	HF	HF	54	LF	HF	HF
23	HF	HF	PF	55	LF	HF	PF
24	HF	HF	LF	56	LF	HF	LF
25	HF	PF	WK	57	LF	PF	WK
26	HF	PF	HF	58	LF	PF	HF
27	HF	PF	PF	59	LF	PF	PF
28	HF	PF	LF	60	LF	PF	LF
29	HF	LF	WK	61	LF	LF	WK
30	HF	LF	HF	62	LF	LF	HF
31	HF	LF	PF	63	LF	LF	PF
32	HF	LF	LF	64	LF	LF	LF

Table 7.1: Fuel rig system scenarios

Each scenario listed in the table is examined and the patterns recorded from the sensor readings for the flows on the outflow lines of each of the tank sections and the level in each tank (see Section 7.4.1.5.2). The system scenarios for the key variables are used in the analysis to identify the section or sections in which a failure has occurred.

7.4.1.5.2 Potential Patterns for Key Variables

The measurements from the flow transmitters in the system are used to build up a flow rate history at their particular locations over a period of time. These can be used to identify overall system pattern behaviour. Readings from the level transmitters in each of the tanks are also used in this analysis. The level patterns obtained are used to determine the amount of fluid flow or rate of change of height of fluid in each tank and illustrates how the reading has changed over time, from which the rate of change can be determined. Each flow transmitter on the fuel rig can measure the exact flow rate at that particular point in the system. The readings from the transmitters are used to build up a pattern to indicate what type of flow or level change is occurring, if any.

Due to the complexity of the problem, the number of possible combinations of different patterns for all of the sensors is too large to deal with in the ACTIVE operating mode. This mode is divided into 'phases' that are defined depending upon the level of fluid in the collector tank in order to overcome this, as shown in Table 7.2.

	Scenarios	MAIN FT0130	MAIN LEVEL LT0110	WING FT0230	WING LEVEL LT0210	COLLECTOR FT0330	COLLECTOR LEVEL LT0310
ACTIVEPHASE1 ($T_1 < L_C <$ RL)	1, 2, 13, 14, 49, 50, 61, 62		RL		RL		RL T1
ACTIVEPHASE2 ($L_C = T_1$)	1, 2, 5, 6, 49, 50, 53, 54		RL		RL PSO		RL T1 T2
ACTIVEPHASE3 ($T_2 < L_C < T_1$)	1, 2, 13, 14, 49, 50, 61, 62		RL		PSO		RL T1 T2
ACTIVEPHASE4 ($L_C = T_2$)	1, 2, 13, 14, 17, 18, 29, 30		RL PSO		PSO		RL T1 T2
ACTIVEPHASE5 (PSO $< L_C < T_2$)	1, 2, 13, 14, 49, 50, 61, 62		PSO		PSO		RL T1 T2 PSO
ACTIVEPHASE6 ($L_C =$ PSO)	1, 4, 13, 16, 49, 52, 61, 64		PSO		PSO		PSO

Table 7.2: Expected sensor patterns for outflow lines and level in each tank in the ACTIVE operating mode

Note that only the overall shape of the trend in each pattern is investigated rather than the exact match of results. When ACTIVE, the operating mode is split into six phases defined by the level of fluid in the collector tank. These phases each have a set of expected sensor readings for the key process variables. The expected plots for the transmitters on the outflow lines of each of the tanks are shown in Table 7.2 (L_C indicates the level of water in the collector tank). The expected plots from these are compared with actual patterns obtained in order to highlight any initial deviations. Main and wing tank levels are also included in order to aid in pinpointing any deviations that may otherwise be missed within these tanks themselves.

Expected plots for the DORMANT mode are shown in Table 7.3. When DORMANT all flow transmitters should be indicating 'no flow' and levels should remain constant. There is only one expected outcome for this particular operating mode.

	Scenarios	MAIN FT0130	MAIN LEVEL LT0110	WING FT0230	WING LEVEL LT0210	COLLECTOR FT0330	COLLECTOR LEVEL LT0310
DORMANT ($L_C =$ RL)	1, 4, 13, 16, 49, 52, 61, 64		RL		RL		RL

Table 7.3: Expected sensor patterns for outflow lines and level in each tank in the DORMANT operating mode

Expected behaviour can be obtained through a number of scenarios for each set of expected readings. In each case, however, it is scenario 1 that is the only one in which the system can be working correctly producing the expected readings and level patterns. The remaining possibilities all contain unrevealed failures, the symptoms for which are masked, but flow within the system carries on as required.

7.4.1.5.3 Identification of Scenario Causes for Key Variables

At any given point in time the set of patterns from the sensors for the key variables must indicate that the system is in at least one of the 64 scenarios listed in Table 7.1. A list of scenarios can be obtained for each of the sets of valid sensor patterns identified for the system and given phase. Scenarios can be used to identify more than one set of sensor patterns. Example plots that can indicate the scenarios 1, 17 and 49 are shown in Table 7.4 for phase 1.

Scenario 1(a) is the expected set of patterns when in ACTIVE phase 1. Scenario 1(b) illustrates that the same scenario can be valid for a different set of patterns - in this case the level in the main tank is non-linearly decreasing indicating that there is a problem with the main tank itself. This is a similar case for 17(a) and 17(b) in which a non-linearly decreasing level in the wing tank indicates a problem with this tank. For some scenarios, for instance 1(a) and 49(a) or 1(b) and 49(b), the observed sensor reading patterns are the same.

Scenario	MAIN FT0130	MAIN LEVEL LT0110	WING FT0230	WING LEVEL LT0210	COLLECTOR FT0330	COLLECTOR LEVEL LT0310
1(a) (WK, WK, WK)		RL		RL		RL TI
1(b) (WK, WK, WK)		RL		RL		RL TI
17(a) (HF, WK, WK)		RL PSO		RL		RL TI
17(b) (HF, WK, WK)		RL PSO		RL		RL TI
49(a) (LF, WK, WK)		RL		RL		RL TI
49(b) (LF, WK, WK)		RL		RL		RL TI

Table 7.4: Possible system readings and their potential scenarios when the system is in the ACTIVE operating mode

There are 508 unique valid combinations of sensor reading patterns when the system is ACTIVE (for each phase) and 829 when in the DORMANT operating mode for the key variables.

7.4.1.6 System Scenarios and Potential Patterns for Other Process Variables

The information from the scenarios and the patterns for the key variables are used in the analysis to indicate the sections of the system in which a failure has occurred. Once this/these sections have been identified the analysis can then focus on obtaining the actual cause. This is carried out by investigating each section with a potential deviation individually. The process of identifying the possible system scenarios is now repeated for each section.

7.4.1.6.1 System Scenarios for Other Process Variables

A set of scenarios applicable to each of the system sections has been developed. As before each flow sensor gives a set of readings indicating the flow at that point in the section. A plot of the results can be determined from these reading, which can be used to match the sensor plot to the possible system scenarios. The sensor plot can indicate whether that part of the system is functioning normally (WK), failed in a mode that causes high flow (HF), failed resulting in partial flow (PF) or if it is failed in a mode that causes low flow (LF). There are 2276 different potential valid scenarios that can occur within a section when investigating both lines within a section - 676 when a section is WK, 356 possibilities for HF, 568 possibilities for PF and 676 LF indicated from a section outflow. The scenarios for HF on the outflow line are shown in Tables 7.5 to 7.7. When investigating just one line there are 204 valid potential scenarios. These are shown - for all section outflows WK, HF, PF and LF - in Tables 7.8 and 7.9.

System Scenarios - Both Lines

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
677	HF	WK	WK	WK	WK	WK
678	HF	WK	WK	WK	WK	HF
679	HF	WK	WK	WK	WK	PF
680	HF	WK	WK	WK	WK	LF
681	HF	WK	WK	WK	HF	WK
682	HF	WK	WK	WK	HF	HF
683	HF	WK	WK	WK	HF	PF
684	HF	WK	WK	WK	HF	LF
685	HF	WK	WK	WK	PF	WK
686	HF	WK	WK	WK	PF	HF
687	HF	WK	WK	WK	PF	PF
688	HF	WK	WK	WK	PF	LF

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
689	HF	WK	WK	WK	LF	WK
690	HF	WK	WK	WK	LF	HF
691	HF	WK	WK	WK	LF	PF
692	HF	WK	WK	WK	LF	LF
693	HF	WK	WK	HF	WK	WK
694	HF	WK	WK	HF	WK	HF
695	HF	WK	WK	HF	WK	PF
696	HF	WK	WK	HF	WK	LF
697	HF	WK	WK	HF	LF	WK
698	HF	WK	WK	HF	LF	HF
699	HF	WK	WK	HF	LF	PF
700	HF	WK	WK	HF	LF	LF

Table 7.5: Fuel rig system scenarios for a tank section - both lines - 1

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
701	HF	WK	WK	PF	WK	WK
702	HF	WK	WK	PF	WK	HF
703	HF	WK	WK	PF	WK	PF
704	HF	WK	WK	PF	WK	LF
705	HF	WK	WK	PF	PF	WK
706	HF	WK	WK	PF	PF	HF
707	HF	WK	WK	PF	PF	PF
708	HF	WK	WK	PF	PF	LF
709	HF	WK	WK	PF	LF	WK
710	HF	WK	WK	PF	LF	HF
711	HF	WK	WK	PF	LF	PF
712	HF	WK	WK	PF	LF	LF
713	HF	WK	WK	LF	WK	WK
714	HF	WK	WK	LF	WK	HF
715	HF	WK	WK	LF	WK	PF
716	HF	WK	WK	LF	WK	LF
717	HF	WK	WK	LF	HF	WK
718	HF	WK	WK	LF	HF	HF
719	HF	WK	WK	LF	HF	PF
720	HF	WK	WK	LF	HF	LF
721	HF	WK	WK	LF	PF	WK
722	HF	WK	WK	LF	PF	HF
723	HF	WK	WK	LF	PF	PF
724	HF	WK	WK	LF	PF	LF
725	HF	WK	WK	LF	LF	WK
726	HF	WK	WK	LF	LF	HF
727	HF	WK	WK	LF	LF	PF
728	HF	WK	WK	LF	LF	LF
729	HF	WK	HF	WK	WK	WK
730	HF	WK	HF	WK	WK	HF
731	HF	WK	HF	WK	WK	PF
732	HF	WK	HF	WK	WK	LF
733	HF	WK	HF	WK	HF	WK
734	HF	WK	HF	WK	HF	HF
735	HF	WK	HF	WK	HF	PF
736	HF	WK	HF	WK	HF	LF
737	HF	WK	HF	WK	PF	WK
738	HF	WK	HF	WK	PF	HF
739	HF	WK	HF	WK	PF	PF
740	HF	WK	HF	WK	PF	LF
741	HF	WK	HF	WK	LF	WK
742	HF	WK	HF	WK	LF	HF
743	HF	WK	HF	WK	LF	PF
744	HF	WK	HF	WK	LF	LF
745	HF	WK	HF	HF	WK	WK
746	HF	WK	HF	HF	WK	HF
747	HF	WK	HF	HF	WK	PF
748	HF	WK	HF	HF	WK	LF
749	HF	WK	HF	HF	LF	WK
750	HF	WK	HF	HF	LF	HF
751	HF	WK	HF	HF	LF	PF
752	HF	WK	HF	HF	LF	LF
753	HF	WK	HF	PF	WK	WK
754	HF	WK	HF	PF	WK	HF
755	HF	WK	HF	PF	WK	PF
756	HF	WK	HF	PF	WK	LF
757	HF	WK	HF	PF	PF	WK
758	HF	WK	HF	PF	PF	HF
759	HF	WK	HF	PF	PF	PF
760	HF	WK	HF	PF	PF	LF
761	HF	WK	HF	PF	LF	WK
762	HF	WK	HF	PF	LF	HF
763	HF	WK	HF	PF	LF	PF
764	HF	WK	HF	PF	LF	LF
765	HF	WK	HF	LF	WK	WK
766	HF	WK	HF	LF	WK	HF
767	HF	WK	HF	LF	WK	PF
768	HF	WK	HF	LF	WK	LF
769	HF	WK	HF	LF	HF	WK
770	HF	WK	HF	LF	HF	HF
771	HF	WK	HF	LF	HF	PF
772	HF	WK	HF	LF	HF	LF
773	HF	WK	HF	LF	PF	WK
774	HF	WK	HF	LF	PF	HF
775	HF	WK	HF	LF	PF	PF
776	HF	WK	HF	LF	PF	LF
777	HF	WK	HF	LF	LF	WK
778	HF	WK	HF	LF	LF	HF
779	HF	WK	HF	LF	LF	PF
780	HF	WK	HF	LF	LF	LF
781	HF	WK	PF	WK	WK	WK
782	HF	WK	PF	WK	WK	HF
783	HF	WK	PF	WK	WK	PF

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
784	HF	WK	PF	WK	WK	LF
785	HF	WK	PF	WK	HF	WK
786	HF	WK	PF	WK	HF	HF
787	HF	WK	PF	WK	HF	PF
788	HF	WK	PF	WK	HF	LF
789	HF	WK	PF	LF	WK	WK
790	HF	WK	PF	LF	WK	HF
791	HF	WK	PF	LF	WK	PF
792	HF	WK	PF	LF	WK	LF
793	HF	WK	PF	LF	HF	WK
794	HF	WK	PF	LF	HF	HF
795	HF	WK	PF	LF	HF	PF
796	HF	WK	PF	LF	HF	LF
797	HF	WK	LF	WK	WK	WK
798	HF	WK	LF	WK	WK	HF
799	HF	WK	LF	WK	WK	PF
800	HF	WK	LF	WK	WK	LF
801	HF	WK	LF	WK	HF	WK
802	HF	WK	LF	WK	HF	HF
803	HF	WK	LF	WK	HF	PF
804	HF	WK	LF	WK	HF	LF
805	HF	WK	LF	PF	WK	WK
806	HF	WK	LF	PF	WK	HF
807	HF	WK	LF	PF	WK	PF
808	HF	WK	LF	PF	WK	LF
809	HF	WK	LF	LF	WK	WK
810	HF	WK	LF	LF	WK	HF
811	HF	WK	LF	LF	WK	PF
812	HF	WK	LF	LF	WK	LF
813	HF	WK	LF	LF	HF	WK
814	HF	WK	LF	LF	HF	HF
815	HF	WK	LF	LF	HF	PF
816	HF	WK	LF	LF	HF	LF
817	HF	HF	WK	WK	WK	WK
818	HF	HF	WK	WK	WK	HF
819	HF	HF	WK	WK	WK	PF
820	HF	HF	WK	WK	WK	LF
821	HF	HF	WK	WK	HF	WK
822	HF	HF	WK	WK	HF	HF
823	HF	HF	WK	WK	HF	PF
824	HF	HF	WK	WK	HF	LF
825	HF	HF	WK	LF	WK	WK
826	HF	HF	WK	LF	WK	HF
827	HF	HF	WK	LF	WK	PF
828	HF	HF	WK	LF	WK	LF
829	HF	HF	WK	LF	HF	WK
830	HF	HF	WK	LF	HF	HF
831	HF	HF	WK	LF	HF	PF
832	HF	HF	WK	LF	HF	LF
833	HF	HF	LF	WK	WK	WK
834	HF	HF	LF	WK	WK	HF
835	HF	HF	LF	WK	WK	PF
836	HF	HF	LF	WK	WK	LF
837	HF	HF	LF	WK	HF	WK
838	HF	HF	LF	WK	HF	HF
839	HF	HF	LF	WK	HF	PF
840	HF	HF	LF	WK	HF	LF
841	HF	HF	LF	LF	WK	WK
842	HF	HF	LF	LF	WK	HF
843	HF	HF	LF	LF	WK	PF
844	HF	HF	LF	LF	WK	LF
845	HF	HF	LF	LF	HF	WK
846	HF	HF	LF	LF	HF	HF
847	HF	HF	LF	LF	HF	PF
848	HF	HF	LF	LF	HF	LF
849	HF	PF	WK	WK	WK	WK
850	HF	PF	WK	WK	WK	HF
851	HF	PF	WK	WK	WK	PF
852	HF	PF	WK	WK	WK	LF
853	HF	PF	WK	WK	HF	WK
854	HF	PF	WK	WK	HF	HF
855	HF	PF	WK	WK	HF	PF
856	HF	PF	WK	WK	HF	LF
857	HF	PF	WK	LF	WK	WK
858	HF	PF	WK	LF	WK	HF
859	HF	PF	WK	LF	WK	PF
860	HF	PF	WK	LF	WK	LF
861	HF	PF	WK	LF	HF	WK
862	HF	PF	WK	LF	HF	HF
863	HF	PF	WK	LF	HF	PF
864	HF	PF	WK	LF	HF	LF
865	HF	PF	PF	WK	WK	WK
866	HF	PF	PF	WK	WK	HF

Table 7.6: Fuel rig system scenarios for a tank section - both lines - 2

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
867	HF	PF	PF	WK	WK	PF
868	HF	PF	PF	WK	WK	LF
869	HF	PF	PF	WK	HF	WK
870	HF	PF	PF	WK	HF	HF
871	HF	PF	PF	WK	HF	PF
872	HF	PF	PF	WK	HF	LF
873	HF	PF	PF	LF	WK	WK
874	HF	PF	PF	LF	WK	HF
875	HF	PF	PF	LF	WK	PF
876	HF	PF	PF	LF	WK	LF
877	HF	PF	PF	LF	HF	WK
878	HF	PF	PF	LF	HF	HF
879	HF	PF	PF	LF	HF	PF
880	HF	PF	PF	LF	HF	LF
881	HF	PF	LF	WK	WK	WK
882	HF	PF	LF	WK	WK	HF
883	HF	PF	LF	WK	WK	PF
884	HF	PF	LF	WK	WK	LF
885	HF	PF	LF	WK	HF	WK
886	HF	PF	LF	WK	HF	HF
887	HF	PF	LF	WK	HF	PF
888	HF	PF	LF	WK	HF	LF
889	HF	PF	LF	LF	WK	WK
890	HF	PF	LF	LF	WK	HF
891	HF	PF	LF	LF	WK	PF
892	HF	PF	LF	LF	WK	LF
893	HF	PF	LF	LF	HF	WK
894	HF	PF	LF	LF	HF	HF
895	HF	PF	LF	LF	HF	PF
896	HF	PF	LF	LF	HF	LF
897	HF	LF	WK	WK	WK	WK
898	HF	LF	WK	WK	WK	HF
899	HF	LF	WK	WK	WK	PF
900	HF	LF	WK	WK	WK	LF
901	HF	LF	WK	WK	HF	WK
902	HF	LF	WK	WK	HF	HF
903	HF	LF	WK	WK	HF	PF
904	HF	LF	WK	WK	HF	LF
905	HF	LF	WK	WK	PF	WK
906	HF	LF	WK	WK	PF	HF
907	HF	LF	WK	WK	PF	PF
908	HF	LF	WK	WK	PF	LF
909	HF	LF	WK	WK	LF	WK
910	HF	LF	WK	WK	LF	HF
911	HF	LF	WK	WK	LF	PF
912	HF	LF	WK	WK	LF	LF
913	HF	LF	WK	HF	WK	WK
914	HF	LF	WK	HF	WK	HF
915	HF	LF	WK	HF	WK	PF
916	HF	LF	WK	HF	WK	LF
917	HF	LF	WK	HF	LF	WK
918	HF	LF	WK	HF	LF	HF
919	HF	LF	WK	HF	LF	PF
920	HF	LF	WK	HF	LF	LF
921	HF	LF	WK	PF	WK	WK
922	HF	LF	WK	PF	WK	HF
923	HF	LF	WK	PF	WK	PF
924	HF	LF	WK	PF	WK	LF
925	HF	LF	WK	PF	PF	WK
926	HF	LF	WK	PF	PF	HF
927	HF	LF	WK	PF	PF	PF
928	HF	LF	WK	PF	PF	LF
929	HF	LF	WK	PF	LF	WK
930	HF	LF	WK	PF	LF	HF
931	HF	LF	WK	PF	LF	PF
932	HF	LF	WK	PF	LF	LF
933	HF	LF	WK	LF	WK	WK
934	HF	LF	WK	LF	WK	HF
935	HF	LF	WK	LF	WK	PF
936	HF	LF	WK	LF	WK	LF
937	HF	LF	WK	LF	HF	WK
938	HF	LF	WK	LF	HF	HF
939	HF	LF	WK	LF	HF	PF
940	HF	LF	WK	LF	HF	LF
941	HF	LF	WK	LF	PF	WK
942	HF	LF	WK	LF	PF	HF
943	HF	LF	WK	LF	PF	PF
944	HF	LF	WK	LF	PF	LF
945	HF	LF	WK	LF	LF	WK
946	HF	LF	WK	LF	LF	HF
947	HF	LF	WK	LF	LF	PF
948	HF	LF	WK	LF	LF	LF
949	HF	LF	HF	WK	WK	WK

Scenario	MAIN SECTION	RECYCLE LINE L1	MAIN LINE L1	RECYCLE LINE L2	MAIN LINE L2	DRAIN LINE
950	HF	LF	HF	WK	WK	HF
951	HF	LF	HF	WK	WK	PF
952	HF	LF	HF	WK	WK	LF
953	HF	LF	HF	WK	HF	WK
954	HF	LF	HF	WK	HF	HF
955	HF	LF	HF	WK	HF	PF
956	HF	LF	HF	WK	HF	LF
957	HF	LF	HF	WK	PF	WK
958	HF	LF	HF	WK	PF	HF
959	HF	LF	HF	WK	PF	PF
960	HF	LF	HF	WK	PF	LF
961	HF	LF	HF	WK	LF	WK
962	HF	LF	HF	WK	LF	HF
963	HF	LF	HF	WK	LF	PF
964	HF	LF	HF	WK	LF	LF
965	HF	LF	HF	HF	WK	WK
966	HF	LF	HF	HF	WK	HF
967	HF	LF	HF	HF	WK	PF
968	HF	LF	HF	HF	WK	LF
969	HF	LF	HF	HF	LF	WK
970	HF	LF	HF	HF	LF	HF
971	HF	LF	HF	HF	LF	PF
972	HF	LF	HF	HF	LF	LF
973	HF	LF	HF	PF	WK	WK
974	HF	LF	HF	PF	WK	HF
975	HF	LF	HF	PF	WK	PF
976	HF	LF	HF	PF	WK	LF
977	HF	LF	HF	PF	PF	WK
978	HF	LF	HF	PF	PF	HF
979	HF	LF	HF	PF	PF	PF
980	HF	LF	HF	PF	PF	LF
981	HF	LF	HF	PF	LF	WK
982	HF	LF	HF	PF	LF	HF
983	HF	LF	HF	PF	LF	PF
984	HF	LF	HF	PF	LF	LF
985	HF	LF	HF	LF	WK	WK
986	HF	LF	HF	LF	WK	HF
987	HF	LF	HF	LF	WK	PF
988	HF	LF	HF	LF	WK	LF
989	HF	LF	HF	LF	HF	WK
990	HF	LF	HF	LF	HF	HF
991	HF	LF	HF	LF	HF	PF
992	HF	LF	HF	LF	HF	LF
993	HF	LF	HF	LF	PF	WK
994	HF	LF	HF	LF	PF	HF
995	HF	LF	HF	LF	PF	PF
996	HF	LF	HF	LF	PF	LF
997	HF	LF	HF	LF	LF	WK
998	HF	LF	HF	LF	LF	HF
999	HF	LF	HF	LF	LF	PF
1000	HF	LF	HF	LF	LF	LF
1001	HF	LF	PF	WK	WK	WK
1002	HF	LF	PF	WK	WK	HF
1003	HF	LF	PF	WK	WK	PF
1004	HF	LF	PF	WK	WK	LF
1005	HF	LF	PF	WK	HF	WK
1006	HF	LF	PF	WK	HF	HF
1007	HF	LF	PF	WK	HF	PF
1008	HF	LF	PF	WK	HF	LF
1009	HF	LF	PF	LF	WK	WK
1010	HF	LF	PF	LF	WK	HF
1011	HF	LF	PF	LF	WK	PF
1012	HF	LF	PF	LF	WK	LF
1013	HF	LF	PF	LF	HF	WK
1014	HF	LF	PF	LF	HF	HF
1015	HF	LF	PF	LF	HF	PF
1016	HF	LF	PF	LF	HF	LF
1017	HF	LF	LF	WK	WK	WK
1018	HF	LF	LF	WK	WK	HF
1019	HF	LF	LF	WK	WK	PF
1020	HF	LF	LF	WK	WK	LF
1021	HF	LF	LF	WK	HF	WK
1022	HF	LF	LF	WK	HF	HF
1023	HF	LF	LF	WK	HF	PF
1024	HF	LF	LF	WK	HF	LF
1025	HF	LF	LF	LF	WK	WK
1026	HF	LF	LF	LF	WK	HF
1027	HF	LF	LF	LF	WK	PF
1028	HF	LF	LF	LF	WK	LF
1029	HF	LF	LF	LF	HF	WK
1030	HF	LF	LF	LF	HF	HF
1031	HF	LF	LF	LF	HF	PF
1032	HF	LF	LF	LF	HF	LF

Table 7.7: Fuel rig system scenarios for a tank section - both lines - 3

System Scenarios - One Line

Scenario	MAIN SECTION	RECYCLE LINE L1/L2	MAIN LINE L1/L2	DRAIN LINE
1	WK	WK	WK	WK
2	WK	WK	WK	HF
3	WK	WK	WK	PF
4	WK	WK	WK	LF
5	WK	WK	HF	WK
6	WK	WK	HF	HF
7	WK	WK	HF	PF
8	WK	WK	HF	LF
9	WK	WK	PF	WK
10	WK	WK	PF	HF
11	WK	WK	PF	PF
12	WK	WK	PF	LF
13	WK	WK	LF	WK
14	WK	WK	LF	HF
15	WK	WK	LF	PF
16	WK	WK	LF	LF
17	WK	HF	WK	WK
18	WK	HF	WK	HF
19	WK	HF	WK	PF
20	WK	HF	WK	LF
21	WK	HF	LF	WK
22	WK	HF	LF	HF
23	WK	HF	LF	PF
24	WK	HF	LF	LF
25	WK	PF	WK	WK
26	WK	PF	WK	HF
27	WK	PF	WK	PF
28	WK	PF	WK	LF
29	WK	PF	LF	WK
30	WK	PF	LF	HF
31	WK	PF	LF	PF
32	WK	PF	LF	LF
33	WK	LF	WK	WK
34	WK	LF	WK	HF
35	WK	LF	WK	PF
36	WK	LF	WK	LF
37	WK	LF	HF	WK
38	WK	LF	HF	HF
39	WK	LF	HF	PF
40	WK	LF	HF	LF
41	WK	LF	PF	WK
42	WK	LF	PF	HF
43	WK	LF	PF	PF
44	WK	LF	PF	LF
45	WK	LF	LF	WK
46	WK	LF	LF	HF
47	WK	LF	LF	PF
48	WK	LF	LF	LF
49	HF	WK	WK	WK
50	HF	WK	WK	HF
51	HF	WK	WK	PF
52	HF	WK	WK	LF
53	HF	WK	HF	WK
54	HF	WK	HF	HF
55	HF	WK	HF	PF
56	HF	WK	HF	LF
57	HF	WK	PF	WK
58	HF	WK	PF	HF
59	HF	WK	PF	PF
60	HF	WK	PF	LF
61	HF	WK	LF	WK
62	HF	WK	LF	HF
63	HF	WK	LF	PF
64	HF	WK	LF	LF
65	HF	HF	WK	WK
66	HF	HF	WK	HF
67	HF	HF	WK	PF
68	HF	HF	WK	LF
69	HF	HF	LF	WK
70	HF	HF	LF	HF
71	HF	HF	LF	PF
72	HF	HF	LF	LF
73	HF	PF	WK	WK
74	HF	PF	WK	HF
75	HF	PF	WK	PF
76	HF	PF	WK	LF
77	HF	PF	PF	WK
78	HF	PF	PF	HF
79	HF	PF	PF	PF
80	HF	PF	PF	LF
81	HF	PF	LF	WK
82	HF	PF	LF	HF
83	HF	PF	LF	PF
84	HF	PF	LF	LF
85	HF	LF	WK	WK
86	HF	LF	WK	HF
87	HF	LF	WK	PF
88	HF	LF	WK	LF
89	HF	LF	HF	WK
90	HF	LF	HF	HF
91	HF	LF	HF	PF
92	HF	LF	HF	LF
93	HF	LF	PF	WK
94	HF	LF	PF	HF
95	HF	LF	PF	PF
96	HF	LF	PF	LF
97	HF	LF	LF	WK
98	HF	LF	LF	HF
99	HF	LF	LF	PF
100	HF	LF	LF	LF
101	PF	WK	WK	WK
102	PF	WK	WK	HF
103	PF	WK	WK	PF
104	PF	WK	WK	LF
105	PF	WK	HF	WK
106	PF	WK	HF	HF
107	PF	WK	HF	PF
108	PF	WK	HF	LF
109	PF	WK	PF	WK
110	PF	WK	PF	HF
111	PF	WK	PF	PF
112	PF	WK	PF	LF
113	PF	WK	LF	WK
114	PF	WK	LF	HF
115	PF	WK	LF	PF
116	PF	WK	LF	LF
117	PF	HF	WK	WK
118	PF	HF	WK	HF
119	PF	HF	WK	PF
120	PF	HF	WK	LF
121	PF	HF	LF	WK
122	PF	HF	LF	HF
123	PF	HF	LF	PF
124	PF	HF	LF	LF
125	PF	PF	WK	WK
126	PF	PF	WK	HF
127	PF	PF	WK	PF
128	PF	PF	WK	LF
129	PF	PF	PF	WK
130	PF	PF	PF	HF
131	PF	PF	PF	PF
132	PF	PF	PF	LF
133	PF	PF	LF	WK
134	PF	PF	LF	HF
135	PF	PF	LF	PF
136	PF	PF	LF	LF
137	PF	LF	WK	WK
138	PF	LF	WK	HF
139	PF	LF	WK	PF
140	PF	LF	WK	LF
141	PF	LF	HF	WK
142	PF	LF	HF	HF
143	PF	LF	HF	PF
144	PF	LF	HF	LF
145	PF	LF	PF	WK
146	PF	LF	PF	HF
147	PF	LF	PF	PF
148	PF	LF	PF	LF
149	PF	LF	LF	WK
150	PF	LF	LF	HF
151	PF	LF	LF	PF
152	PF	LF	LF	LF
153	LF	WK	WK	WK
154	LF	WK	WK	HF
155	LF	WK	WK	PF
156	LF	WK	WK	LF
157	LF	WK	HF	WK
158	LF	WK	HF	HF
159	LF	WK	HF	PF
160	LF	WK	HF	LF
161	LF	WK	PF	WK
162	LF	WK	PF	HF
163	LF	WK	PF	PF
164	LF	WK	PF	LF
165	LF	WK	LF	WK
166	LF	WK	LF	HF
167	LF	WK	LF	PF
168	LF	WK	LF	LF
169	LF	HF	WK	WK
170	LF	HF	WK	HF

Table 7.8: Fuel rig system scenarios for a tank section - one line - 1

Scenario	MAIN SECTION	RECYCLE LINE L1/L2	MAIN LINE L1/L2	DRAIN LINE
171	LF	HF	WK	PF
172	LF	HF	WK	LF
173	LF	HF	LF	WK
174	LF	HF	LF	HF
175	LF	HF	LF	PF
176	LF	HF	LF	LF
177	LF	PF	WK	WK
178	LF	PF	WK	HF
179	LF	PF	WK	PF
180	LF	PF	WK	LF
181	LF	PF	PF	WK
182	LF	PF	PF	HF
183	LF	PF	PF	PF
184	LF	PF	PF	LF
185	LF	PF	LF	WK
186	LF	PF	LF	HF
187	LF	PF	LF	PF

Scenario	MAIN SECTION	RECYCLE LINE L1/L2	MAIN LINE L1/L2	DRAIN LINE
188	LF	PF	LF	LF
189	LF	LF	WK	WK
190	LF	LF	WK	HF
191	LF	LF	WK	PF
192	LF	LF	WK	LF
193	LF	LF	HF	WK
194	LF	LF	HF	HF
195	LF	LF	HF	PF
196	LF	LF	HF	LF
197	LF	LF	PF	WK
198	LF	LF	PF	HF
199	LF	LF	PF	PF
200	LF	LF	PF	LF
201	LF	LF	LF	WK
202	LF	LF	LF	HF
203	LF	LF	LF	PF
204	LF	LF	LF	LF

Table 7.9: Fuel rig system scenarios for a tank section - one line - 2

7.4.1.6.2 Potential Patterns for Subsystem Variables

As for the key variables the system pattern behaviour is identified from the flow and level sensors. Deviated readings from the key variables are examined in more detail. These are used to highlight any problems within each tank section and once a deviation is indicated an investigation of the appropriate subsystem variables can take place. This will indicate any inconsistencies within the appropriate section. It may be concluded that more than one section has a deviation, therefore these would need to be investigated separately for each.

To investigate the patterns for the main tank section knowledge of those expected are required. These are shown in Tables 7.10 to 7.13 for the ACTIVE mode for phases 1 to 6, and for the DORMANT mode respectively, for both lines.

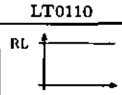
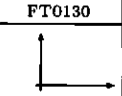
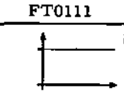
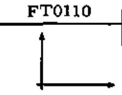
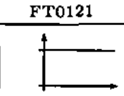
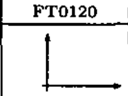
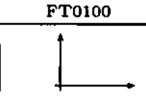
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100
ACTIVEPHASE1/2/3							
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 157, 160, 169, 172, 173, 176, 177, 180, 209, 212, 221, 224, 225, 228, 229, 232, 261, 264, 273, 276, 277, 280, 281, 284, 1609, 1612, 1621, 1624, 1625, 1628, 1629, 1632, 1765, 1768, 1777, 1780, 1781, 1784, 1785, 1788, 1817, 1820, 1829, 1832, 1833, 1836, 1837, 1840, 1869, 1872, 1881, 1884, 1885, 1888, 1889, 1892						

Table 7.10: Expected sensor patterns for the main tank section
in the ACTIVE operating mode when in phases 1, 2 and 3 - both lines

These tables include the expected patterns when using the redundant line in the main tank section. In the event of failure occurring in the main stream line the system functionality is such that it will switch to the redundant line, therefore the system will be able to carry on working as required with the failure present. The redundant line is only used in the event of a failure causing no flow out of the subsystem as a result of an unexpected key flow variable pattern for the given tank section. Therefore the expected patterns for the system will also change, as shown in the second line Table 7.11. The scenarios when using the redundant line will be dependent upon the set of patterns exhibited from the main line.

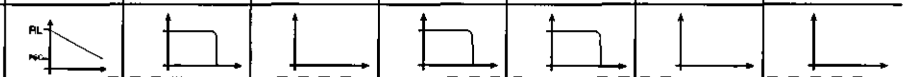
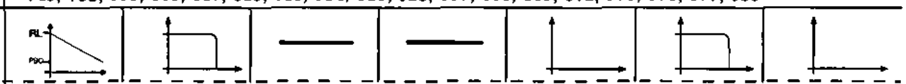
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100
ACTIVEPHASE4							
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980						
Operating Using Redundant Line							
Scenarios	Dependent upon patterns on Line L1.						

Table 7.11: Expected sensor patterns for the main tank section in the ACTIVE operating mode when in phase 4 - both lines

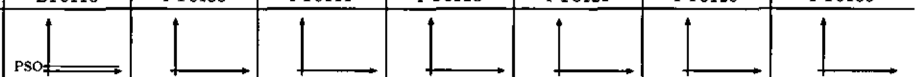
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100
ACTIVEPHASE5/6							
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284						

Table 7.12: Expected sensor patterns for the main tank section in the ACTIVE operating mode when in phases 5 and 6 - both lines

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100
DORMANT							
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284						

Table 7.13: Expected sensor patterns for the main tank section in the DORMANT operating mode - both lines

A deviation within a tank section may be the result of a failure on one or potentially both of the stream lines. In the case where there is a failure in the main stream line and the redundant line is being used the failed line can be investigated as the occurrence of a failure at this point in the system would be known. Tables 7.14 to 7.17 show the expected patterns for one line (L1) in the main tank.

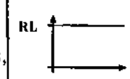
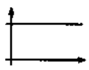
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100
ACTIVEPHASE1/2/3	1, 4, 13, 16, 33, 36, 37, 40, 153, 156, 165, 168, 169, 172, 173, 176					

Table 7.14: Expected sensor patterns for the main tank section in the ACTIVE operating mode when in phases 1, 2 and 3 - one line

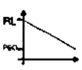
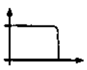
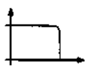
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100
ACTIVEPHASE4	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196					

Table 7.15: Expected sensor patterns for the main tank section in the ACTIVE operating mode when in phase 4 - one line

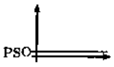
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100
ACTIVEPHASE5/6	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204					

Table 7.16: Expected sensor patterns for the main tank section in the ACTIVE operating mode when in phases 5 and 6 - one line

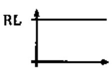
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100
DORMANT	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204					

Table 7.17: Expected sensor patterns for the main tank section in the DORMANT operating mode - one line

In a similar manner as carried out for the sets of patterns obtained from the key variables for each set of patterns a list of possible scenarios are obtained.

7.4.1.7 Fault Tree Construction

7.4.1.7.1 Fault Tree Development

Non-coherent fault trees are drawn to determine the causality of deviations from expected sensor readings within the system. A tree is developed for each transmitter in a subsystem by taking into consideration the system operating mode and the potential causes of failure within this part, thus restricting the boundary of causes to that particular section of the system.

Non-coherent fault trees are constructed for deviations from the expected observations for the flow transmitters on the drainage line and each of the streams L1 and L2. Due to the symmetry of the structure the potential causes of failure for each of these streams are the same, the only difference being the numbering on each line. When the transmitters are known to be functioning correctly this information is incorporated into the analysis by drawing a success tree. Fault trees are also drawn for the level transmitter in each subsystem, indicating a loss of containment within the tank itself or another part of the subsystem.

Fault trees have been constructed for the failure modes of each flow and level transmitter in a tank unit, details of which can be found in Appendix D. The structure of the main, wing and collector tanks are the same, therefore only fault trees for the main tank are illustrated. Fault trees are drawn for high, partial and low flow from each flow transmitter and constant, linearly decreasing and non-linearly decreasing levels from the level transmitters. Success trees have also been developed for when the system is functioning correctly.

7.4.1.7.2 Possible Component Failures

To apply fault tree analysis to any system all possible failures that could occur for each of the system components must be defined. Table 7.18 contains a list of possible component failures and their code for the main, wing and collector tanks in the system. The notation 'i' represents the particular subsystem and 'j' the component number within the subsystem. As all sensors are assumed to be reliable the possible failures for flow and levels sensors have been omitted.

Code		Component Failure
IVP0ij0FC ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 Fails Closed
IVP0ij0FO ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 Fails Open
IVP0ij0FS ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 Fails Stuck
IVP0ij0B ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 is Blocked
IVP0ij0PB ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 is Partially Blocked
IVP0ij0L ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Powered Isolation Valve IVP0ij0 is Leaking
PSV0ij0ISC ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 Fails Incorrectly Set Closed
PSV0ij0ISO ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 Fails Incorrectly Set Open
PSV0ij0FS ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 Fails Stuck
PSV0ij0B ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 is Blocked
PSV0ij0PB ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 is Partially Blocked
PSV0ij0L ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Pressure Sprung Relief Valve PSV0ij0 is Leaking
BP0ij0B ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Back Pressure Valve BP0ij0 is Blocked
BP0ij0PB ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Back Pressure Valve BP0ij0 is Partially Blocked
BP0ij0L ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Back Pressure Valve BP0ij0 is Leaking
PP0ij0FSO ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Peristaltic Pump PP0ij0 Fails Shut Off
PP0ij0FM ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Peristaltic Pump PP0ij0 Fails Mechanically
PP0ij0L ($1 \le i \le 3$) ($1 \le j \le 2$)	-	Peristaltic Pump PP0ij0 is Leaking
PP0ij0FO ($01 \le i \le 3$) ($1 \le j \le 2$)	-	Peristaltic Pump PP0ij0 Fails On
P0ijB ($1 \le i \le 3$) ($01 \le j \le 25$)	-	Pipe P0ij is Blocked
P0ijF ($1 \le i \le 3$) ($01 \le j \le 25$)	-	Pipe P0ij is Fractured
P0ijPB ($1 \le i \le 3$) ($01 \le j \le 25$)	-	Pipe P0ij is Partially Blocked
P0ijL ($1 \le i \le 3$) ($01 \le j \le 25$)	-	Pipe P0ij is Leaking
TK0i10R ($1 \le i \le 3$)	-	Tank TK0i10 is Ruptured
TK0i10L ($1 \le i \le 3$)	-	Tank TK0i10 is Leaking
CT0ij0T ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Controller CT0ij0 fails reading True
CT0ij0F ($1 \le i \le 3$) ($1 \le j \le 3$)	-	Controller CT0ij0 fails reading False

Table 7.18: Potential component failures for the fuel rig system

7.4.2 Fault Identification - The Application Stage

7.4.2.1 Identification of Actual Patterns

The patterns in Table 7.2 are used to indicate a problem in the overall system operation in the ACTIVE mode. Assume for example there is no flow out of the main tank when it is required in phase ACTIVE4. The system has been working as required up to this point. The expected and actual readings obtained for the system key variables are as shown in Table 7.19 along with the potential scenarios for the patterns from the key variables.

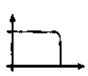
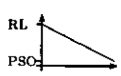
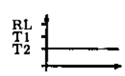
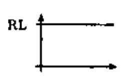
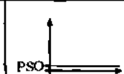
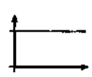
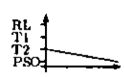
	Scenarios	MAIN FT0130	MAIN LEVEL LT0110	WING FT0230	WING LEVEL LT0210	COLLECTOR FT0330	COLLECTOR LEVEL LT0310
ACTIVE4 ($L_C = T_2$) Expected Patterns	1, 2, 13, 14 17, 18, 29, 30						
ACTIVE4 ($L_C < T_2$) Actual Patterns	49, 52, 61, 64						

Table 7.19: Actual sensor patterns for the overall system in ACTIVE phase 4

7.4.2.2 Identification of Deviated Key Variables

Table 7.19 shows that the level in the collector tank is decreasing below threshold T_2 when it should be constant. The pattern from the main tank level (LT0110) at this point should be linearly decreasing and no flow out of the main tank is also indicating a problem. Key variable patterns not consistent with those expected for ACTIVE4 are FT0130, LT0110 and LT0310. An unchangeable level in the main tank indicates there is water present, unless a sensor has failed. Therefore there is at least one pattern not consistent with those expected in Table 7.19 for the given phase. A list of potential scenarios for the system is given. By forming a fault tree structure for the scenarios the problem can be identified as being present in the subsystem containing the main tank.

7.4.2.3 TOP Event Structure Construction

A comparison of subsystem sensors is made and patterns identified in the same way as for the overall system. Each stream is investigated to ascertain the potential failure cause. Table 7.20 shows an example of expected and actual sensor patterns for the working (L1) and redundant (L2) lines.

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100
ACTIVE4 Expected Patterns	RL PSO						
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980						
Actual Patterns	RL						
Scenarios	1869, 1872, 1881, 1884, 1885, 1888, 1889, 1892						
Operating Using Redundant Line	RL PSO		—	—			
Scenarios	1869, 1872, 1873, 1876, 1905, 1908, 1909, 1912						
Actual Patterns	RL						
Scenarios	1889, 1892						

Table 7.20: Expected and actual sensor patterns for the main tank subsystem when flow is expected on the outflow line

In this example actual patterns from the system are indicating that both lines L1 and L2 have flow on the recycle lines but not out on each of the stream lines. The flow sensor on the drain line is the only one giving the expected pattern for the tank section.

Figures 7.5 and 7.6 show the structure for scenarios 1889 and 1892 respectively together with the corresponding level pattern.

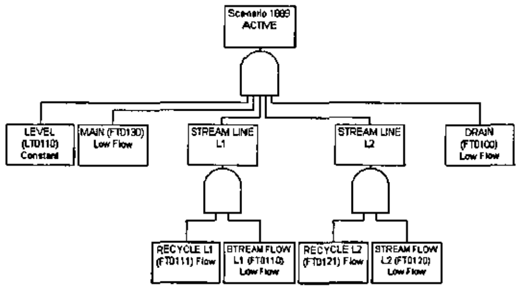


Figure 7.5: Structure for Scenario 1889 in the ACTIVE operating mode phase 4

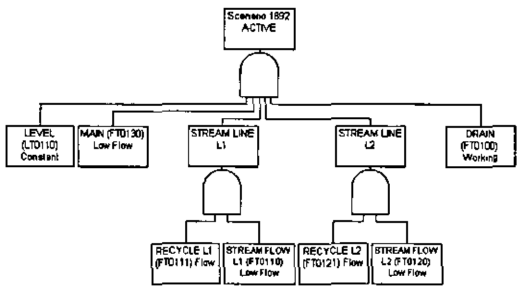


Figure 7.6: Structure for Scenario 1892 in the ACTIVE operating mode phase 4

Both deviated and working readings are included in the diagrams. The scenarios for each set of patterns are then combined using an 'OR' gate to form the overall TOP event for the sensor and level patterns, as shown in Figure 7.7.

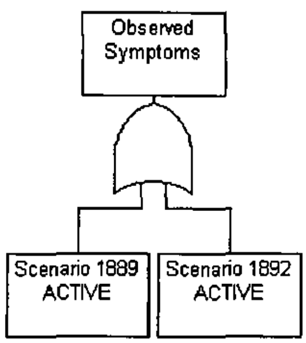


Figure 7.7: TOP event structure for example

7.4.2.4 Prime Implicants

A qualitative analysis of the fault tree in Figure 7.7 will produce a set of prime implicants that highlight the potential causes of failure for these given subsystem symptoms, along with the working components. An example prime implicant obtained in this case is:

$\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112L}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111L}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0109F}}$
$.\overline{\mathrm{P0109L}}.\overline{\mathrm{BP0120L}}.\overline{\mathrm{IVP0120L}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}$
$.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}}.\overline{\mathrm{PP0120L}}.\overline{\mathrm{P0118B}}$
$.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0118PB}}.\overline{\mathrm{P0118L}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119PB}}.\overline{\mathrm{P0119L}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0120PB}}.\overline{\mathrm{PSV0120ISC}}$
$.\overline{\mathrm{PSV0120B}}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106L}}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105L}}.\overline{\mathrm{P0104F}}$
$.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{BP0110L}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}$
$.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0115B}}$
$.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{PSV0110ISC}}$
$.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{IVP0180S}}.\overline{\mathrm{IVP0180FO}}.\overline{\mathrm{CT0130T}}.\overline{\mathrm{TK0110L}}.\overline{\mathrm{TK0110R}}$

This prime implicant is of order 85. In total 66 prime implicants are obtained, two of order 85 and 64 of order 86.

7.4.2.5 Potential Causes of System Failure

Any working component states are removed at this stage from the prime implicants by performing a coherent approximation, to give a list of potential causes of failure. The potential causes for the example are shown in Table 7.21. Post connection failures are failures that occur after the two streams join. The method has correctly identified all the potential causes of failure in this particular case.

Post Connection Failures		Failure on Stream L1		Failure on Stream L2
1) P0113B	OR	1) P0103B	AND	1) P0109B
2) P0114B		2) P0104B		2) P0110B
		3) P0105B		3) P0111B
		4) P0106B		4) P0112B
		5) BP0110B		5) BP0120B
		6) IVP0110FC		6) IVP0120FC
		7) IVP0110B		7) IVP0120B
		8) CT0110F		8) CT0120F
Potential Failure Causes (Order 1): 2		Potential Failure Causes (Order 2): 64		

Table 7.21: Potential causes of failure

Table 7.21 shows there are 66 potential causes of system failure, 2 of order 1, as shown in the first column of the table and 64 of second order that are obtained by ANDing together the failures on stream L1 with those on L2. For instance, P0113B is a single failure and P0103B.IVP0120FC is a multiple failure containing two faults.

7.4.2.6 Ranking of Failure Modes

Measures of importance [29] are used to identify the most likely cause of failure. The unavailability of each component is calculated using Equation 3.35. The Fussell-Vesely measure of minimal cut set importance, shown in Equation 3.49 is then used to rank the cut sets that were obtained using the method. Table 7.22 shows the unavailability of each component, assuming that the deviation occurred at $t = 3600$s.

Component Failure	Conditional Failure Rate	Unavailability
P0103B-P0106B, P0109B-P0114B	1.0×10^{-8}	3.5999351×10^{-5}
BP0110B, BP0120B	1.9×10^{-7}	6.83766123×10^{-4}
IVP0110FC, IVP0120FC	1.5×10^{-7}	5.39854225×10^{-4}
IVP0110B, IVP0120B	2.5×10^{-7}	8.9959512×10^{-4}
CT0110F, CT0120F	7.4×10^{-6}	2.6288285×10^{-2}

Table 7.22: Component failure rate and unavailability

Q_{SYS} is determined using the Rare Event Approximation (see Section 3.6.2.2.2), and for this example was found to be $Q_{SYS} = 8.874151607\times10^{-4}$. Using the Fussell-Vesely measure of of minimal cut set importance has shown that the most likely cause of failure is CT0110F.CT0120F - controller CT0110 and CT0120 both failing reading FALSE - in this case.

7.5 Results

The example used in Section 7.4.2 has illustrated how the method obtains the potential causes of failure for the actual set of patterns identified from the system when a deviation in sub-mode ACTIVE4 occurs. This indicates that flow from the main tank section is required but is not occurring. There are 8 other sets of patterns for both lines in the main tank section that could have shown the deviation in the key variables of failure to output fluid, as illustrated in Table 7.23. The first two lines of the table are the required patterns out of the main tank section using the main and redundant lines respectively.

For a given set of symptoms the most ideal outcome would be to obtain one potential cause of failure, of single order. In reality however this will not always be the case. The more components there are in a potential cause the less likely it will be the reason for failure. Therefore the potential causes of failure obtained are up to and including those of order 3 to reduce the complexity of the analysis. The effectiveness index I_E that was used in the water tank system is used to indicate how well the method has been scaled up for use on the fuel rig.

Possible Pattern	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL PSO							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
-	RL PSO							-	-	-
Scenarios	1869, 1872, 1873, 1876, 1905, 1908, 1909, 1912									
1	RL							9	9	9
Scenarios	1777, 1780, 1813, 1816, 2245, 2248, 2281, 2284									
2	RL							24	24	30
Scenarios	1785, 1788, 2253, 2256									
3	RL							192	192	240
Scenarios	1797, 1800, 2265, 2268									
4	RL							24	24	30
Scenarios	1881, 1884, 1917, 1920									
5	RL							66	66	66
Scenarios	1889, 1892									
6	RL							528	528	528
Scenarios	1901, 1904									
7	RL							192	192	240
Scenarios	2037, 2040									
8	RL							528	528	528
Scenarios	2045, 2048, 2073, 2076									
9	RL							128	128	128
Scenarios	2057, 2060									
							Effectiveness Index I_E	0.911		

Table 7.23: Possible flow and level patterns for the main tank when there is a constant level and no flow out of the tank in the ACTIVE operating mode - both lines

Results have been obtained considering the possible patterns that could occur for the given key variables in this case. There are four sets of patterns for which the actual number of potential failure causes are not obtained. These are numbers 2, 3, 4, and 7. Pattern 4 is a 'mirror image' of 2 and similarly with 7 and 3. The results obtained in patterns 1, 5, 6, 8 and 9 are correct for the given readings. The results give an effectiveness index $I_E = 0.911$, indicating that although not all possible component failures were identified the method has still achieved a very good result.

In pattern 2 there are 24 potential causes of failure obtained, but 30 actual possibilities. On line L1 no flow at both FT0111 on the recycle line and at FT0110 are caused by peristaltic pump PP0110 failing shut off (PP0110FSO), or pipes P0101 or P0102 being blocked (P0101B, P0102B). On line L2 there is flow at FT0121 and no flow at FT0120. This situation is caused by either a blockage in pipes P0109, P0110, P0111 or P0112 (P0109B, P0110B, P0111B, P0112B) or powered isolation valve IVP0120 failing closed, blocked or controller CT0120 causing the valve to be closed (IVP0120FC, IVP0120B, CT0120F). This gives the 24 possibilities that were obtained by the method. In addition to these failures on line L2 there could also be a blockage in pipes P0113 or P0114 (P0113B, P0114B), but these failures are hidden because they are a potential cause for both lines and get cancelled out by the expected behaviour at FT0111. This problem was also the reason for the non-identification of all failures in patterns 3, 4 and 7.

A deviation could occur in the system, but it could continue with normal operation using system redundancy. Assume the key variables indicate as before and the conclusion drawn is that there is a problem in the main tank section. In the event of a failure on the main stream line, the system will use the redundant line. There will however be a pattern from the main stream line sensors indicating that a problem has occurred, resulting in the use of the secondary line. In this case switching to the redundant line in the tank may enable it to carry on as required. Regardless of whether the system carries on working or not the failed line can be investigated to ascertain the problem. There are 3 sets of patterns that could be indicated from the given key variables, these are shown in Table 7.24.

The first line shows the required patterns out of the main tank section using the main stream line. There are 3 possible sets of patterns that can result in no flow out of the tank and no change in the level. In all cases the correct number of potential causes of failure have been obtained. The effectiveness index of 1.000 indicates that the method has worked well in this case when investigating one line.

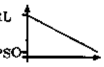
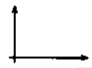
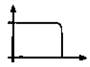
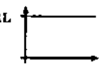
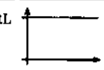
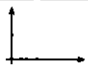
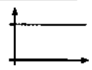
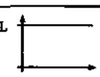
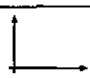
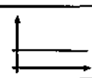
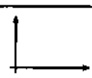
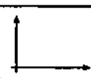
Possible Pattern	Scenarios	LEVEL L1 LT0110	MAIN FLOW L1 FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8, 33, 36, 37, 40, 153, 156, 157, 160, 189, 192, 193, 196	RL PSO 					-	-	-
1	165, 168, 201, 204	RL 					3	3	3
2	173, 176	RL 					10	10	10
3	185, 188	RL 					80	80	80
					Effectiveness Index I_E		1.000		

Table 7.24: Possible flow and level patterns for the main tank when there is a constant level and no flow out of the tank in the ACTIVE operating mode - one line

Results are shown in Appendix E for various key variable patterns that lead to a failure within the main tank section to demonstrate the method in the ACTIVE mode. Additional results in the DORMANT mode are shown in Appendix F for the situation where it has been concluded that a problem has occurred in the main tank causing unwanted flow. The results include patterns exhibiting unexpected flow, low flow and no flow when in the ACTIVE operating mode and unexpected flow or low flow when in the DORMANT mode.

7.6 Discussion of Results

7.6.1 Overview

The results have given an average effectiveness index of $I_E = 0.973$ for investigating both lines together and $I_E = 0.886$ when looking at a single line in the ACTIVE operating mode. These show that in both cases the method has been very effective at obtaining the potential causes of failure for the given subsystem. DORMANT results, shown in Appendix F have yielded an average effectiveness index of $I_E = 1.000$ for both lines and $I_E = 1.000$ looking at a single line respectively, therefore strengthening the performance of the method in both cases. Application to an aircraft is required to determine how effective the method can be on a real system.

Advantages and disadvantages were obtained for looking at lines singularly and together. Investigating both lines was more likely to give higher order possibilities, therefore breaking the analysis up into separate lines in this case would enable the analysis to focus in on the actual cause. Investigating one line at a time reduces the complexity of the problem. The results show that there are in general less potential causes of failure when looking at a single line. Also the combining of less sensor readings compared to investigating both lines reduces the time taken to obtained a diagnosis. A single line was not always enough to find the cause, as the line under investigation indicated that this was not causing the overall failure on the outflow of the subsystem. Therefore the second line in this instance would also need investigation.

When there is unexpected no flow out of the tank it is advantageous to look at each of the lines separately because it is known that the line on which flow is expected has failed. If unexpected flow occurs then either of the two lines could have caused the failure. Therefore when one line is investigated in this situation it may not necessarily be the one that contains the failure. If it is deduced that the line being investigated does not contain the cause then the second line can be examined in further detail.

7.6.2 Limited Order

The likelihood of a potential cause being the actual failure decreases the larger the cut set order. Therefore, only potential causes of up to order 3 were obtained during the analysis. This has indicated that some of the sensor patterns, although valid, are not very likely to occur. Limiting the order has therefore enabled the method to focus in on the most probable faults and highlight scenarios that are not very likely to appear in the analysis. Possible causes of higher order were more likely to occur when looking at both lines together. In these cases it would be better to investigate lines separately to reduce this and focus in on the failed area. As used in the analysis of the water tank system, in the event that there is more than one possible fault, measures of importance are used to obtain the overall cause of failure.

7.6.3 Subsystems

The breaking down of the system into smaller sections has meant that the method can be utilised on larger scale systems. Monitoring the key process variables enabled any deviation in the patterns to be highlighted in the event of a problem within each subsystem. Once a subsystem has been pinpointed as having a failure it can then be investigated further to focus in on the most likely cause.

7.6.4 Complexity of the Fault Trees

The fault trees shown in Appendix D for the fuel rig system in the majority of cases are quite large, especially compared to those used in the water tank system. Another approach that could be used to potentially reduce the complexity of the analysis would be to just indicate the components that could have potentially failed for the system rather than how. This would reduce the size of the fault trees. However, different failure states will result in different types of sensor readings, for instance a blockage in a pipe may affect the system differently to a fracture. NOT logic is used to remove any deviations both within the fault trees and by indicating what component states should not be failed when a sensor is not deviated. Therefore alternatively the same type of failures could be grouped together such as all blockages in pipes that could be the result of the same sensor deviation. This would reduce the size of the fault trees, by identifying the location and type of failure rather than the actual cause. A list of potential causes of failure could be drawn up for each type of failure. Once the area in which the failure location is obtained and the type of failure found, the most likely cause could be ascertained from the list using measure of importance.

7.6.5 Sensor Failures

The sensors in the system were assumed to be reliable. A failure in a sensor could however be indicated in the system by any patterns that are deemed invalid, for instance the occurrence of overall flow out of the tank, but no flow on either of the two lines before this. A set of patterns that cannot occur would be identified.

If a set of patterns were to occur that were not valid then this would signify the occurrence of a problem with one or more of the sensors within the system or subsystem under investigation and that these rather than any of the other components should be investigated.

7.7 Summary

- The dynamic method is extended and described by applying it to a model based on a fuel rig from BAE Systems. This features redundancy and is a larger system than previously considered.
- In the majority of cases the method has effectively identified the potential causes of failure for both the ACTIVE and the DORMANT operating modes.

- Application to a real aircraft fuel system is required to validate the method's effectiveness and scalability to an even larger example.

Chapter 8

Application to Aircraft Fuel Systems

8.1 Introduction

The fault tree method so far has only been demonstrated on small, simple systems. This chapter describes the characteristics of aircraft fuel systems, indicating any similarities and difficulties that may be faced when applying the fault diagnostic method.

8.2 Aircraft Systems

The overview of a general aircraft system has highlighted a number of issues that may be encountered. This section looks at these issues and how this will impact on the application of the fault diagnostic method. The Modelling and Preparation Stage (MPS) steps described in Section 7.2.1 were:

1. System division
2. Identification of system sensors
3. Identification of key process variables
4. System scenario identification
5. System operating modes and assumptions
6. System scenarios

7. Expected pattern behaviour for key variables

8. Expected pattern behaviour for other variables

9. Fault tree construction

The method is now applied to an example aircraft fuel system.

8.2.1 Nimrod MRA4

The Nimrod is the world's only jet powered maritime patrol and anti-submarine aircraft developed in the 1960s through extensive modification of the de Havilland Comet, which was the world's first jetliner. It was created in order to replace the Royal Air Force's piston-engined Avro Shackleton as their primary maritime patrol aircraft and has been so since the early 1970s. The most recent design of the Nimrod is the MRA4, the main roles for which are maritime reconnaissance, anti-submarine warfare, anti-surface unit warfare, and search and rescue. The fuel system is comprised of thirteen tanks supplying four engines, a typical structure for the Nimrod MRA4 is as illustrated in Figure 8.1 [81]. The aim, as for any aircraft fuel system, is to provide an adequate supply of fuel to each of the four engines for the duration of flight.

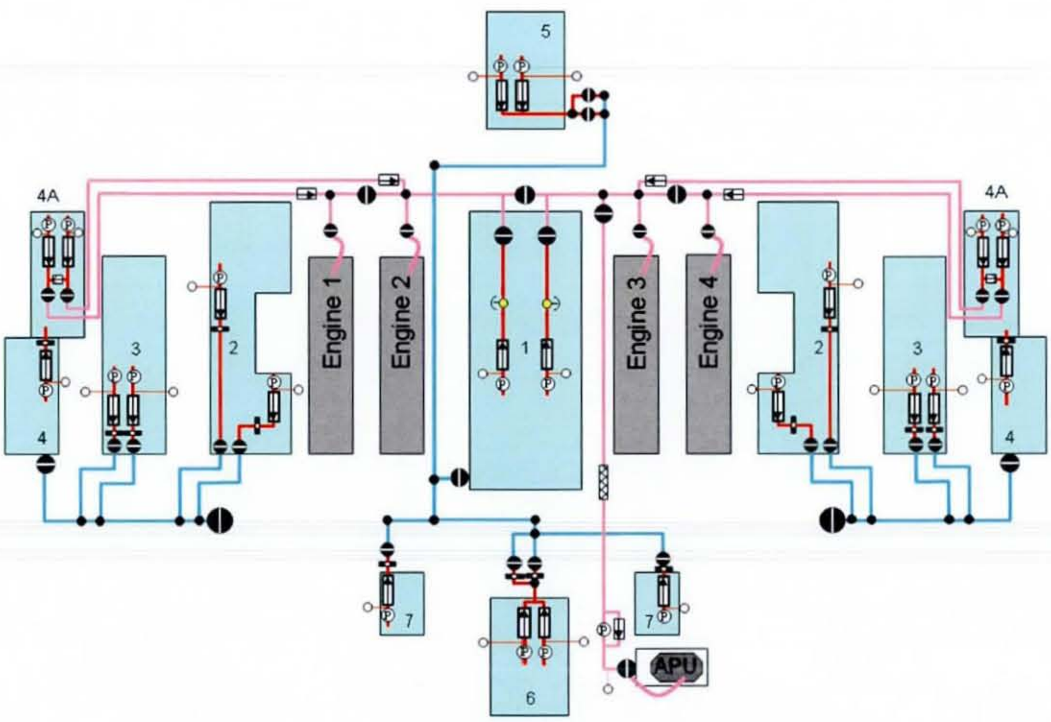


Figure 8.1: The Nimrod MRA4 Fuel System

The fuel system consists of three collecting or feed tanks used to supply four engines via a fuel feed gallery. In addition each wing contains three tanks that feed into a collecting tank, and similarly in there are four feeding tanks within the fuselage. A surge tank is located in each of the wings, which is part of the venting system. These are used to prevent fuel from being lost in the event of any entering the venting system.

8.2.1.1 System Component Description

8.2.1.1.1 Fuel Tanks

Tanks 1, 5 and 6 are located within the main fuselage and two of each of the remaining tanks labelled 2, 3, 4, 4A and 7 are located within each of the wings, as shown in Figure 8.1. Those labelled 4A are pod tanks and are directly linked to their adjacent tank 4, from which 4A is gravity fed fuel. As a result, the total fuel within tanks 4 and 4A is gauged together. The three collector tanks are tank 1 and 4/4A within each of the wings. When the system is in normal operation tank 1 will feed engines 2 and 3, with tank 4/4A on the left-hand side feeding engine 1 and tank 4/4A on the right-hand side feeding engine 4. Tanks 2, 3, 5, 6 and 7 are transfer tanks as fuel is transferred from these to the tanks feeding the engines.

8.2.1.1.2 Fuel Measurement

The contents of fuel within each tank is measured using capacitance gauge probes. An accurate mass of fuel is obtained from these measurements as well as data from the Enhanced Global-positioning-system Inertial-navigation-unit (EGI), densitometers, which are located in tanks 1, 2 (right-hand side) and 4 (left-hand-side), level sensors and compensators. The mass of each individual tank is displayed and the total amount available is indicated to the pilot. From this, the level of fuel within each tank can also be determined. The information obtained is also used to determine the centre of gravity for the aircraft.

The distribution of fuel within the aircraft is controlled by the Fuel Management System (FUM). The main part of this is the Utilities Systems Management System (USMS). For the majority of time fuel within the system is automatically controlled and managed through USMS computers 1 and 2 using the information obtained from the measurements taken in the Fuel Gauging and Levelling Sensing System (FUG). The aircrew provide manual input in the event of certain malfunctions taking place, and also during refuel, defuel, fuel dumping, fuel transfer and air-to-air refuelling. Temperature sensors are located within each collecting tank to indicate if it is within an acceptable limit. A high temperature could cause the fuel to boil and if it is too low it could result in it waxing, if water is present in the fuel then this could freeze.

8.2.1.1.3 Fuel Galleries

The system contains two main fuel galleries that enable fuel to be pumped between the tanks and on to the engines and auxiliary power unit. An illustration of the fuel system indicating the locations of the two main fuel galleries, labelled 'fuel feed gallery' and 'refuel/transfer gallery', are shown in Figure 8.2 [82]. The fuel feed gallery is fed from collecting tanks 1 and 4AR/L. The refuel/transfer gallery is used to transport fuel to the appropriate collecting tank when the aircraft is in operation.

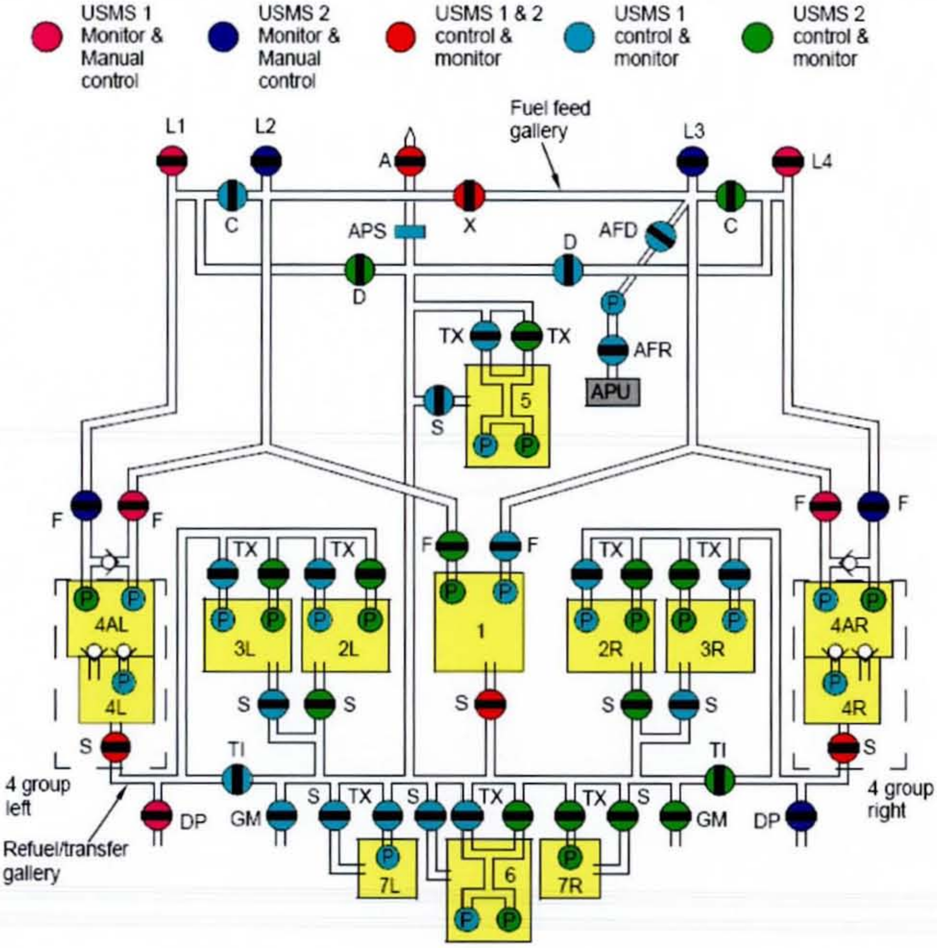


Figure 8.2: Nimrod MRA4 fuel system components

8.2.1.1.4 Fuel Pumps and Valves

Each transfer tank - except for number 7 tanks - contains two transfer pumps (P) and transfer pump valves (TX) so enables the fuel to be transported to the given collecting tank (number 7 tanks contain only one transfer pump and valve). The three collecting tanks (1 and 4) each have two feed pumps (P) and two feed isolate valves (F). In addition, the number 4 tanks also contain a transfer pump to enable fuel to be fed from tank 4 to 4A in the event that gravity feeding is not possible, for instance when these tanks are low on fuel. Non-return valves are located on the lines from each collecting tank to enable fuel to be transferred to the back-up feed line. A component key for the fuel system is shown in Figure 8.3 [82].

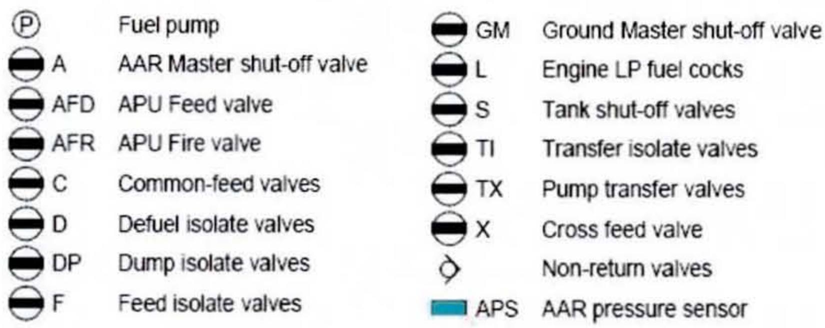


Figure 8.3: Nimrod MRA4 fuel system component key

Each pump within the system is located such that all fuel can be drawn from the tank, even when the aircraft is at an angle. Each pump is able to operate independently as needed. During normal operation both pumps in tank 1 are expected to provide fuel to the engines.

There are number of additional types of valve within the system. Each tank is fitted with a shut-off valve (S) to control the flow of fuel into it. Fuel flow from the aircraft system to the engine system can also be prevented by closing the manually controlled low pressure fuel cocks (L). Common-feed (C) and cross-feed (X) valves enable fuel to be directed to different locations along the fuel feed gallery, and similarly transfer isolate valves (TI) are used to direct fuel along the refuel/transfer gallery to the collecting tanks.

The defuel isolate valves (D) are used during the defuelling and fuel dumping of the aircraft. In addition to this they are also utilised in fuel transfer. The dump isolate valves (DP) are opened when the system is in fuel dumping mode in order to release fuel. Other valves include the ground master shut-off (GM) that are used during ground refuel and defuel, the air-to-air refuelling valve (A) used when the aircraft is being refuelled in the air and the

APU feed valve (AFD), APU fire valve (AFR) and APU fuel pump (P) control fuel flow into the APU. The non-return valves force fuel to flow in one direction and prevent it from going back the other way.

8.2.1.1.5 Fuel System Indicators and Displays

Fuel system data is displayed to the pilots via the fuel system page, the engine warning display and the final fuel selector display.

Fuel System Page This is the main display that gives information regarding the modes of system operation, fuel quantities in each tank, fuel temperature, the presence of any leakages, the low pressure cock status (open or closed), the status of the XFEED, LCOM and RCOM valves (open or closed), pipeline status (presence or absence of fluid), and finally whether the system is in the fuel dump and refuel modes.

Engine Warning Display This displays any warnings that are encountered in the system, such as low levels in fuel tanks and when fuel dumping is taking place.

Final Fuel Display This displays the final fuel that is manually selected by the FINAL FUEL selector.

Multi-Function Control and Display Unit This displays mission information including reports on flight progress, nearest airport locations and possible diversions.

Critical Data Area There is a critical data area on the fuel system page that displays the total amount of fuel flow per hour, the amount of fuel available, reserve fuel, and predicted fuel left once arriving at the chosen destination.

8.2.1.2 Level Transmitter Thresholds

Capacitance probes are located within each of the tanks in order to indicate high and low levels by transmitting the information to the USMS. This information is then used to control the transfer of fuel within the tanks in the system. An illustration of typical principles of the capacitance probe functions for level indication is shown in Figure 8.4 [81]. There are five main thresholds within each tank: 'High-High' (Hi-Hi), 'High' (Hi), 'High-Low' (Hi-Lo), 'Low-High' (Lo-Hi) and 'Low-Low' (Lo-Lo).

Hi-Hi An OVERFILL alert is given when the Hi-Hi level is reached within any tank. This will cause any shut off valves from refuelling appliances (for instance, during air-to-air or ground refuel) to close.

Hi A Hi level reading from any tank will cause its shut off valve to close in order to stop the fuel transfer into the tank.

Hi-Lo A tank's shut off valve will open to enable the transfer of fuel into the tank when the level reaches 'Hi-Lo' or below.

Lo-Hi The Lo-Hi level is that which any tank must be at in order to allow fuel to be transferred from it to another tank within the system. Any level below this and fuel transfer from the given tank cannot be carried out.

Lo-Lo Reaching the level Lo-Lo in any of the tanks will result in the termination of fuel transfer from that particular tank. Fuel transfer will only recommence if the level in the tank rises to the Lo-Hi level.

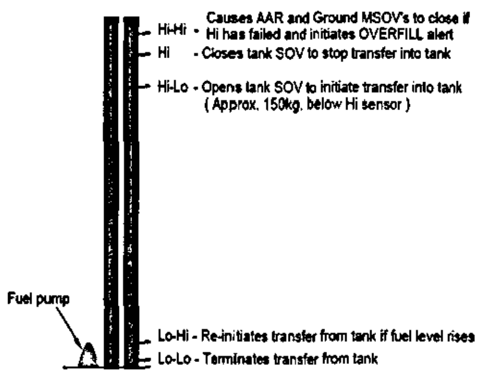


Figure 8.4: Nimrod MRA4 capacitance probe functions for level indication

8.2.2 Modelling and Preparation Stage

8.2.2.1 System Division

For the fault detection process to take place the system described needs to be divided into sections. This will enable the analysis to be broken down and allow failed areas to be focused in on. During normal operation engine 1 is fed by collector tank 4/4A within the left wing of the aircraft, which in turn are fed by transfer tanks 2 and 3. Similarly engine 4 is fed by collector tank 4/4A on the right-hand side of the aircraft, which is fed by transfer tanks 2 and 3 on that side. Finally engines 2 and 3 are fed by collecting tank 1, which collects fuel from transfer tanks numbered 5, 6 and 7. The fuel system transfer is illustrated in Figure 8.5 (based upon the diagram shown in Figure 8.1). The diagram also shows that the system is split into three main sections, each containing a collector tank along with the respective engine or engines being fed from them, and the tanks transferring fuel into them. This will enable the analysis to focus on a collector tank section individually.

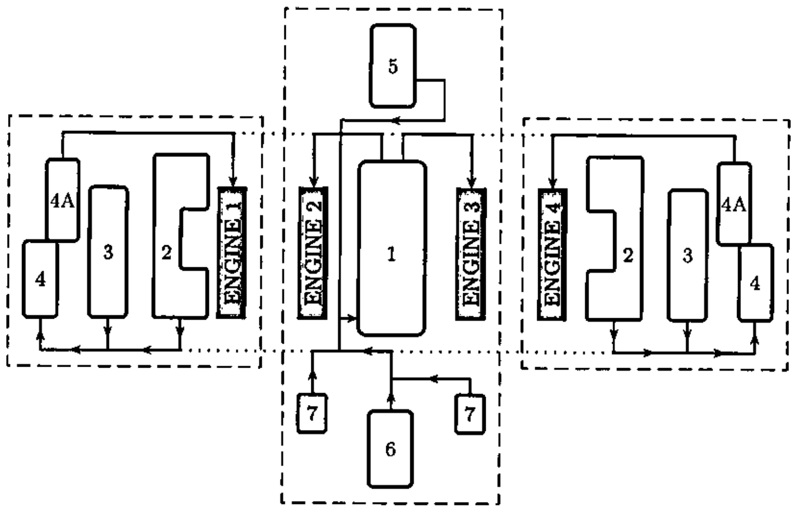


Figure 8.5: The Nimrod MRA4 fuel system sections and direction of transfer

Each of these sections is then divided further into sub-sections containing each tank, as shown in Figures 8.6 and 8.7 for the left wing and the fuselage respectively. Both wings are similar in structure. Tanks 4 and 4A are grouped together as the amount/level of fuel is not gauged separately for each.

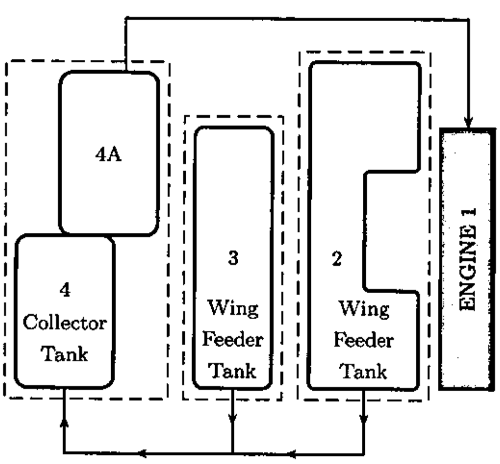


Figure 8.6: Sub-division of the Nimrod MRA4 fuel system for the left wing

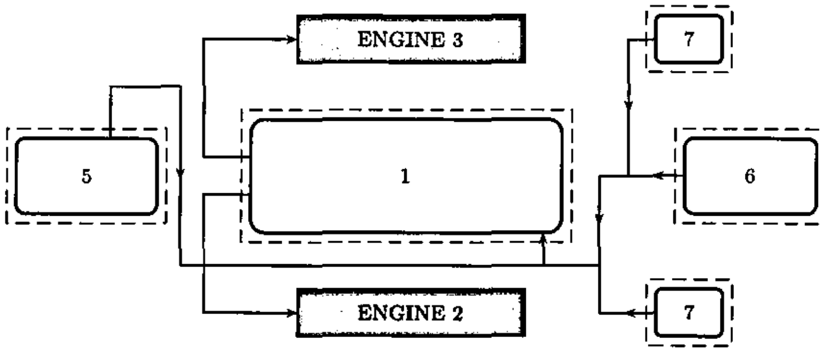


Figure 8.7: Sub-division of the Nimrod MRA4 fuel system for the fuselage

8.2.2.2 Identification of System Sensors

Measurements taken from the system include flow out of the tanks into the engines, and the level within each tank. Each of the tanks contains a series of probes that are used to continuously monitor the level of fuel and pass data to the USMS, as described in more detail in Section 8.2.1.2. This information is combined with other data to determine the overall mass of fuel within each tank and therefore within the whole system. There is a flow transmitter on the line to each engine to indicate that the correct amount of fuel is getting transferred. In addition flow transmitters could be located on each line out of a feed tank and into each of the collecting tanks. These will indicate whether fuel has been successfully transferred from a feed tank into a collector tank. Similarly flow meters could be located to monitor fuel flow to and from other tanks within the system.

8.2.2.3 Key Variables

The key process variables within the system would be the level in each of the collecting tanks and the flows into each of the four engines from the collecting tanks. The level in each of the feeding tanks are also important factors to consider in the system functionality as these could indicate a problem with an individual tank that may otherwise be left undetected. The key process variables will indicate to the operator the occurrence of a failure and can be used to determine in which part or parts the failure or failures are located.

Each wing section in the system contains one engine that is fed by one collecting tank. A wing section therefore contains one key flow transmitter on the respective engine to the collector tank, which contains the key level sensor for this section. The fuselage section contains two engines, which are both fed via separate pumps and lines out of tank 1. In this case there are two key flow transmitter readings and one key level.

8.2.2.4 Operating Modes and Assumptions

8.2.2.4.1 Operating Modes

The major transfer modes in a military aircraft: engine feed and transfer, APU fuel feed, air-to-air refuel, ground refuel or defuel, fuel dumping and shut down.

- *Engine Fuel Feed and Transfer (XFER)* - Fuel is transferred from the tanks to the engines.
- *APU Fuel Feed (APUFEED)* - Fuel is fed from Tank 4R via the number 3 engine gallery to the APU during normal operation.
- *Air-to-Air Refuel (AAR)* - The aircraft is refuelled from another plane whilst in flight via the A valve.
- *Ground Refuel (REFUEL)* - The aircraft is refuelled whilst on the ground.
- *Ground Defuel (DEFUEL)* - The aircraft is defuelled whilst on the ground.
- *Fuel Dump (DUMP)* - Fuel is dumped from the nimrod via the DP valves.
- *Shut Down (DORMANT)* - The system is dormant, therefore no fuel transfer takes place.

For the purposes of illustrating the method the XFER operating mode is examined in more detail.

8.2.2.4.2 Assumptions

The following assumptions have been made for the Nimrod MRA4 fuel system:

- Systems sensors are assumed to be reliable.
- The system will start off with a full level of fuel in each tank if the system is in the XFER, APUFEED, DUMP or DORMANT modes.

8.2.2.5 System Scenarios and Patterns for the Key Process Variables

8.2.2.5.1 System Scenarios

The flow into each engine can be indicated as functioning normally (WK), failed in a mode that causes high flow (HF) (eg: engine low pressure fuel cock valve open), failed resulting in partial flow (PF) (eg: valve partially open) or failed in such a way that results in low flow (LF) (eg: valve closed). If a section of the system is working this indicates that fluid is being provided from that part to the engine or engines as and when required in response to the system state and operating mode. Flow transmitters are located on the feed lines for each engine and are labelled FT0100, FT0200, FT0300 and FT0400 for engines 1 to 4 respectively (see Figures 8.8 and 8.10). Each of the 4 sensors could be functioning in one of the 4 possible ways described above, leading to 256 different potential scenarios that could possibly occur (as $4^4 = 256$). A few examples of the scenarios for these sensor readings are shown in Table 8.1.

Scenario	FT0100	FT0200	FT0300	FT0400
1	WK	WK	WK	WK
2	WK	WK	WK	HF
3	WK	WK	WK	PF
4	WK	WK	WK	LF
...	...	...	...	...

Table 8.1: Nimrod fuel system key variable scenarios

The flow transmitters indicate whether the correct amount of fluid is exiting the given collecting tank from which it is being fed and getting to the engine. Each potential scenario is examined and patterns are recorded from the transmitter readings for the flows on the engine lines for the wing and fuselage sections and the level in each of the collecting tanks that feed the given engine or engines. The system scenarios for the key variables from each section are used in the analysis to identify the section or sections where a failure has occurred.

If all sensors in a system were analysed simultaneously then the amount of data could be too complex to consider, especially on large systems. The method demonstrated on the fuel rig system in Chapter 7 brought about the idea of using a hierarchical approach to analysing a system by focusing on the area of failure using key variable sensors. This involved examining the readings from key sensors and then investigating deviated areas further, thus building up a hierarchy. This is now used on the Nimrod MRA4. The first set of flow sensors within the system to consider (key variable sensors) would be those on the lines from the collecting tanks, along with their level sensors. This information can be used to identify a deviation within a system section from the point of view of it not delivering the correct amount of fuel.

8.2.2.5.2 Potential Patterns for Key Variables

A flow rate history is built up for each of the readings from the flow transmitters in order to identify system pattern behaviour. In addition readings from the level sensors are used to build up level patterns to determine the fluid flow or rate of change of height. These indicate how the level within each collecting tank has changed over time. Both flow and level patterns can therefore be used to determine a change in flow or level at given locations in the system over time. The shape of the trend for each pattern is investigated in each case. The XFER mode has three phases of operation, the expected sensor patterns for each of these are shown in Table 8.2.

	Scenarios	FT0100 FLOW	LT0104L LEVEL	FT0200 FLOW	FT0300 FLOW	LT0201 LEVEL	FT0400 FLOW	LT0404L LEVEL
XFERPhase1	1, 2, 5, 6, 17, 18, 21, 22, 65, 66, 69, 70, 81, 82, 85, 86		HI			HI		HI
XFERPhase3	1, 2, 5, 6, 17, 18, 21, 22, 65, 66, 69, 70, 81, 82, 85, 86		HI LOLO			HI LOLO		HI LOLO
XFERPhase3	1, 4, 13, 16, 49, 52, 61, 64, 193, 196, 205, 208, 241, 244, 253, 256		LOLO			LOLO		LOLO

Table 8.2: Expected key sensor patterns for engine feed lines and level in each collecting tank in the XFER operating mode

A number of scenarios for each set of expected readings can be obtained, however, scenario 1 is the only one in which the system can be working as required. The other scenarios contain potential failures, but these are hidden and the system carries on to seemingly work as required. Any deviation from the expected patterns for each phase indicates that a failure has occurred in some part of the system. At this point the engine that is not being fed properly or a deviation in level in the respective collector tank indicates the section in which the failure has occurred and therefore needs further investigation. If there is more than one deviated section then each needs to be individually analysed in more detail. A set of patterns are valid if they they can occur for any of the possible operating modes. For each of these there will be at least one system scenario exhibited from the 256 outcomes for the 4 sensors and their 4 possible values (see Table 8.1).

8.2.2.6 System Scenarios and Patterns for Each Section

Information from the key variables within the system is used to identified the section or sections of the system in which a failure has taken place. Once the section or sections have been determined analysis can focus on obtaining the cause of failure. A potential deviation within a section is analysed individually using additional sensor readings in the given section.

8.2.2.6.1 Wing Section

Scenarios

A set of scenarios has been developed for each of the wing section within the system using sensors FT0100, FT0104 and FT0102, as shown in Figure 8.8. (Flow transmitter FT0100 is similar to FT0330 in the collector tank section on the fuel rig system, and similarly FT0102 and FT0104 are like FT0130 and FT0230 in the main and wing tank sections).

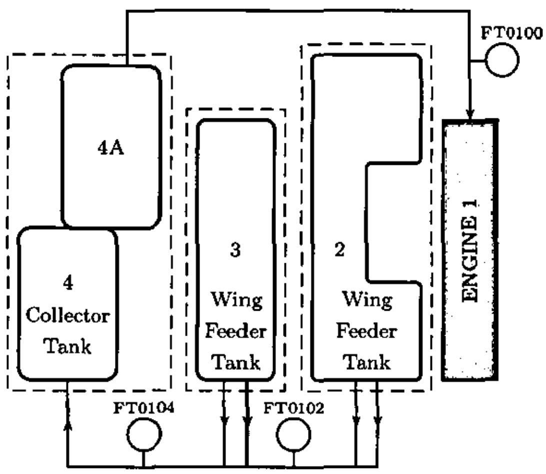


Figure 8.8: Sensors in the wing section

These sensors will indicate to the user the sub-section or sub-sections in which the failure has occurred. There are $4^3 = 64$ different potential scenarios that this part of the system can be in at any given point for the chosen sensor readings. These are obtained from having 3 sensors each with 4 possible values. Examples of the scenarios are shown in Table 8.3.

Scenario	FT0100	FT0104	FT0102
1	WK	WK	WK
2	WK	WK	HF
3	WK	WK	PF
4	WK	WK	LF
...	...	...	...

Table 8.3: Nimrod fuel system wing section scenarios

The 64 scenarios can be used to indicate the area in the wing section in which the deviation or deviations are located. Additional sensors within the system, for instance on the individual lines out of each tank (as in the fuel rig example), can be used to carry out a more in depth investigation into each tank within the wing section. This will lead to the identification of more scenarios for that given system area. For example, there is a flow sensor located on the feed line from wing feeder tank 2, but there could also be flow sensors located on each of the lines out of this tank. Once it has been established that a failure is located in this tank section, investigations can be carried to focus in once again on finding the cause. Figure 8.9 illustrates tank 2 in the left wing section, showing the locations of the sensors in this sub-section.

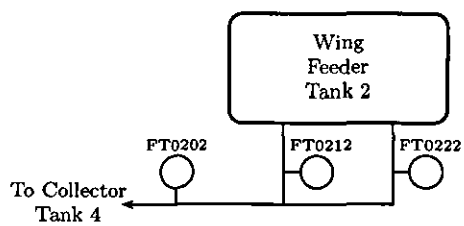


Figure 8.9: Sub-section containing tank 2 in the left wing section

The sub-section shows that in addition to the flow sensor FT0102 on the feed line there are also sensors on the pump lines, labelled FT0112 and FT0122. There are 59 different valid potential scenarios for this sub-section, as shown in Table 8.4.

Scenario	FT0102	FT0112	FT0122	Scenario	FT0102	FT0112	FT0122	Scenario	FT0102	FT0112	FT0122
1	WK	WK	WK	21	HF	HF	WK	41	PF	LF	WK
2	WK	WK	HF	22	HF	HF	HF	42	PF	LF	HF
3	WK	WK	PF	23	HF	HF	PF	43	PF	LF	PF
4	WK	WK	LF	24	HF	HF	LF	44	LF	WK	WK
5	WK	HF	WK	25	HF	PF	WK	45	LF	WK	HF
6	WK	HF	HF	26	HF	PF	HF	46	LF	WK	PF
7	WK	HF	PF	27	HF	LF	WK	47	LF	WK	LF
8	WK	HF	LF	28	HF	LF	HF	48	LF	HF	WK
9	WK	PF	WK	29	PF	WK	WK	49	LF	HF	HF
10	WK	PF	HF	30	PF	WK	HF	50	LF	HF	PF
11	WK	PF	PF	31	PF	WK	PF	51	LF	HF	LF
12	WK	PF	LF	32	PF	WK	LF	52	LF	PF	WK
13	WK	LF	WK	33	PF	HF	WK	53	LF	PF	HF
14	WK	LF	HF	34	PF	HF	HF	54	LF	PF	PF
15	WK	LF	PF	35	PF	HF	PF	55	LF	PF	LF
16	WK	LF	LF	36	PF	HF	LF	56	LF	LF	WK
17	HF	WK	WK	37	PF	PF	WK	57	LF	LF	HF
18	HF	WK	HF	38	PF	PF	HF	58	LF	LF	PF
19	HF	WK	PF	39	PF	PF	PF	59	LF	LF	LF
20	HF	WK	LF	40	PF	PF	LF				

Table 8.4: Nimrod fuel system tank 2 sub-section scenarios

(Flow transmitters FT0112 and FT0122 are in similar locations to FT0110 and FT0120 in the main tank section on the fuel rig system). There should be 64 potential scenarios obtained from 3 sensors having 4 possible outcomes. However, 5 of the possibilities are invalid for the location of the sensor readings, therefore are not included in the table of possibilities. The invalid scenarios are shown in Table 8.5.

Scenario	FT0102	FT0112	FT0122
1	HF	PF	PF
2	HF	PF	LF
3	HF	LF	PF
4	HF	LF	LF
5	PF	LF	LF

Table 8.5: Nimrod fuel system tank 2 invalid sub-section scenarios

Scenarios 1 to 4 in Table 8.5 are invalid because high flow cannot occur at FT0102 if there is only partial or no flow at FT0112 or FT0122, and in scenario 5 partial flow cannot occur when there is only low flow at FT0112 or FT0122.

Patterns

In the same way as for the key variables a set of patterns can be developed from the flow rate and level measurement history for the sensors in the left wing section, as shown in Table 8.6.

	Scenarios	FT0100 FLOW	LT0104 LEVEL	FT0104 FLOW	LT0103 LEVEL	FT0102 FLOW	LT0102 LEVEL
XFERWingPhase1	1, 2, 5, 6 17, 18, 21, 22		HI		HI		HI .789
XFERWingPhase2	1, 4, 5, 8 17, 20, 21, 24		HI		HI LOLO		.789
XFERWingPhase3	1, 2, 5, 6 17, 18, 21, 22		HI		LOLO		.789 LOLO
XFERWingPhase4	1, 4, 13, 16, 17, 20, 29, 32		HI LOLO		LOLO		LOLO
XFERWingPhase5	1, 4, 13, 16, 49, 52, 61, 64		LOLO		LOLO		LOLO

Table 8.6: Expected sensor patterns for the left wing section in the XFER operating mode

The patterns from the wing section will indicate the scenarios that the system could potentially be in. This will highlight the tank or tanks in the section in which there is a problem, therefore showing which require further investigation. A deviation at FT0102 or LT0102 will indicate a problem in tank 2L in the system. This can then be investigated in order to focus in on the possible problem area and determine the possible cause. The patterns and their potential scenarios are shown in Table 8.7.

	Scenarios	FT0102 FLOW	LT0102 LEVEL	FT0112 FLOW	FT0122 FLOW
XFERTank2Phase1	1, 4, 5, 8, 17, 20, 21, 24		HI .789		
XFERTank2Phase2	1, 4, 13, 16, 44, 47, 56, 59		.789		
XFERTank2Phase3	1, 4, 5, 8, 17, 20, 21, 24		.789 LOHI		
XFERTank2Phase4	1, 2, 5, 6, 17, 18, 21, 22		LOHI LOLO		
XFERTank2Phase5	1, 4, 13, 16, 44, 47, 56, 59		LOLO		

Table 8.7: Expected sensor patterns for tank 2 in the left wing section in the XFER operating mode

A fault tree can be constructed for any patterns that deviate from those expected in a given phase in order to ascertain the most likely causes of failure in the system.

8.2.2.6.2 Fuselage Section

Scenarios

A set of scenarios has been developed for the fuselage section in this particular fuel system for the sensors FT0201, FT0200 and FT0300, as shown in Figure 8.10.

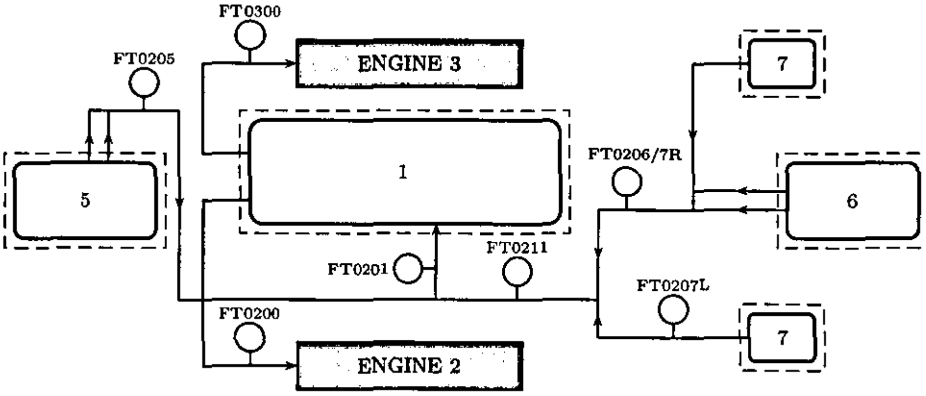


Figure 8.10: Sensors in the fuselage section

The lines that FT0200 and FT0300 are located on lead to engines 2 and 3 respectively, and FT0201 is on the line leading into tank 1 in the same way as provided for each wing section. (Flow transmitter FT0100 is similar to FT0330 in the collector tank section on the fuel rig system, and similarly FT0104 and FT0102 are FT0230 and FT0130 in the main and wing tank sections). A set of 64 scenarios are obtained from the 3 sensors each having 4 possible values, as introduced in Table 8.8.

Scenario	FT0200	FT0300	FT0201
1	WK	WK	WK
2	WK	WK	HF
3	WK	WK	PF
4	WK	WK	LF
...	...	...	...

Table 8.8: Nimrod fuel system fuselage section scenarios

If there is no flow into the collecting tank 1 (FT0201) when required then there must be a failure preventing the transfer of fluid from the feeding tanks. Similarly there could be too much fluid going into the collecting tank. More sensors can be incorporated into the analysis - for instance flow meters FT0205 and FT0211 (see Figure 8.10) - which indicate the fuel flow from the fuselage transfer tanks into the collecting tank. There are 64 different potential scenarios that can be obtained for FT0201, FT0211 and FT0205 (3 sensors each having 4 values). Table 8.9 illustrates some of the scenarios for the given sensor readings. This part of the analysis identifies the area within the section in which the failure has taken place resulting the deviation.

Scenario	FT0201	FT0211	FT0205
1	WK	WK	WK
2	WK	WK	HF
3	WK	WK	PF
4	WK	WK	LF
...	...	...	...

Table 8.9: Nimrod fuel system scenarios for inlet into collecting tank 1

The potential scenarios from this part of the analysis will indicate whether a failure has occurred in the tank 5 section or if there is a problem in tanks 7 right/left (7R/L) or tank 6. If it is indicated that the failure is in either tanks 7 or 6 then scenarios can be developed for FT0201, FT0211, FT0206/7R and FT0207L in the same way as illustrated in order to focus in on the location of the deviation. In this case there will be 256 scenarios obtained from analysing 4 sensors each with 4 possible values ($4^4 = 256$). Some example scenarios for these sensor readings are shown in Table 8.10.

Scenario	FT0201	FT0211	FT0206/7R	FT0207L
1	WK	WK	WK	WK
2	WK	WK	WK	HF
3	WK	WK	WK	PF
4	WK	WK	WK	LF
...	...	...	...	...

Table 8.10: Example Nimrod fuel system scenarios for sub-section containing tanks 6, 7R and 7L - 1

More sensors can be located in the system on the individual lines out of each tank in order to provide a more in depth investigation. For instance, as well as the flow sensor located on the line from wing feeder Tank 5 there could also be flow sensors located on each of the lines out of this tank. If a failure is indicated as being within this tank section, analysis can focus in once again on finding the cause. Figure 8.11 illustrates Tank 5, showing the locations of the sensors in this sub-section.

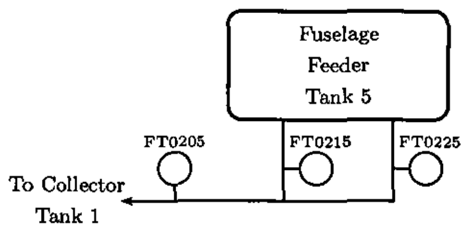


Figure 8.11: Tank 5 in the fuselage section

The sub-section shows that in addition to the flow sensor FT0205 on the feed line there are also sensors on the pump lines, labelled FT0215 and FT0225. There are 236 different valid potential scenarios out of 256 (4^4) for this sub-section, as shown in Tables 8.11 to 8.13. Flow transmitter FT0201 is also included in the analysis as a failure at this point may not be indicated by the other sensors within the section.

Scenario	FT0201	FT0205	FT0215	FT0225
1	WK	WK	WK	WK
2	WK	WK	WK	HF
3	WK	WK	WK	PF
4	WK	WK	WK	LF
5	WK	WK	HF	WK
6	WK	WK	HF	HF
7	WK	WK	HF	PF
8	WK	WK	HF	LF
9	WK	WK	PF	WK
10	WK	WK	PF	HF
11	WK	WK	PF	PF
12	WK	WK	PF	LF
13	WK	WK	LF	WK
14	WK	WK	LF	HF
15	WK	WK	LF	PF

Scenario	FT0201	FT0205	FT0215	FT0225
16	WK	WK	LF	LF
17	WK	HF	WK	WK
18	WK	HF	WK	HF
19	WK	HF	WK	PF
20	WK	HF	WK	LF
21	WK	HF	HF	WK
22	WK	HF	HF	HF
23	WK	HF	HF	PF
24	WK	HF	HF	LF
25	WK	HF	PF	WK
26	WK	HF	PF	HF
27	WK	HF	LF	WK
28	WK	HF	LF	HF
29	WK	PF	WK	WK
30	WK	PF	WK	HF

Table 8.11: Nimrod fuel system tank 5 sub-section scenarios - 1

Scenario	FT0201	FT0205	FT0215	FT0225
31	WK	PF	WK	PF
32	WK	PF	WK	LF
33	WK	PF	HF	WK
34	WK	PF	HF	HF
35	WK	PF	HF	PF
36	WK	PF	HF	LF
37	WK	PF	PF	WK
38	WK	PF	PF	HF
39	WK	PF	PF	PF
40	WK	PF	PF	LF
41	WK	PF	LF	WK
42	WK	PF	LF	HF
43	WK	PF	LF	PF
44	WK	LF	WK	WK
45	WK	LF	WK	HF
46	WK	LF	WK	PF
47	WK	LF	WK	LF
48	WK	LF	HF	WK
49	WK	LF	HF	HF
50	WK	LF	HF	PF
51	WK	LF	HF	LF
52	WK	LF	PF	WK
53	WK	LF	PF	HF
54	WK	LF	PF	PF
55	WK	LF	PF	LF
56	WK	LF	LF	WK
57	WK	LF	LF	HF
58	WK	LF	LF	PF
59	WK	LF	LF	LF
60	HF	WK	WK	WK
61	HF	WK	WK	HF
62	HF	WK	WK	PF
63	HF	WK	WK	LF
64	HF	WK	HF	WK
65	HF	WK	HF	HF
66	HF	WK	HF	PF
67	HF	WK	HF	LF
68	HF	WK	PF	WK
69	HF	WK	PF	HF
70	HF	WK	PF	PF
71	HF	WK	PF	LF
72	HF	WK	LF	WK
73	HF	WK	LF	HF
74	HF	WK	LF	PF
75	HF	WK	LF	LF
76	HF	HF	WK	WK
77	HF	HF	WK	HF
78	HF	HF	WK	PF
79	HF	HF	WK	LF
80	HF	HF	HF	WK
81	HF	HF	HF	HF
82	HF	HF	HF	PF
83	HF	HF	HF	LF
84	HF	HF	PF	WK
85	HF	HF	PF	HF
86	HF	HF	LF	WK
87	HF	HF	LF	HF
88	HF	PF	WK	WK
89	HF	PF	WK	HF
90	HF	PF	WK	PF
91	HF	PF	WK	LF
92	HF	PF	HF	WK
93	HF	PF	HF	HF
94	HF	PF	HF	PF
95	HF	PF	HF	LF
96	HF	PF	PF	WK
97	HF	PF	PF	HF
98	HF	PF	PF	PF
99	HF	PF	PF	LF
100	HF	PF	LF	WK
101	HF	PF	LF	HF
102	HF	PF	LF	PF
103	HF	LF	WK	WK
104	HF	LF	WK	HF
105	HF	LF	WK	PF
106	HF	LF	WK	LF
107	HF	LF	HF	WK
108	HF	LF	HF	HF
109	HF	LF	HF	PF
110	HF	LF	HF	LF
111	HF	LF	PF	WK
112	HF	LF	PF	HF
113	HF	LF	PF	PF
114	HF	LF	PF	LF
115	HF	LF	LF	WK
116	HF	LF	LF	HF
117	HF	LF	LF	PF
118	HF	LF	LF	LF
119	PF	WK	WK	WK
120	PF	WK	WK	HF
121	PF	WK	WK	PF
122	PF	WK	WK	LF

Scenario	FT0201	FT0205	FT0215	FT0225
123	PF	WK	HF	WK
124	PF	WK	HF	HF
125	PF	WK	HF	PF
126	PF	WK	HF	LF
127	PF	WK	PF	WK
128	PF	WK	PF	HF
129	PF	WK	PF	PF
130	PF	WK	PF	LF
131	PF	WK	LF	WK
132	PF	WK	LF	HF
133	PF	WK	LF	PF
134	PF	WK	LF	LF
135	PF	HF	WK	WK
136	PF	HF	WK	HF
137	PF	HF	WK	PF
138	PF	HF	WK	LF
139	PF	HF	HF	WK
140	PF	HF	HF	HF
141	PF	HF	HF	PF
142	PF	HF	HF	LF
143	PF	HF	PF	WK
144	PF	HF	PF	HF
145	PF	HF	LF	WK
146	PF	HF	LF	HF
147	PF	PF	WK	WK
148	PF	PF	WK	HF
149	PF	PF	WK	PF
150	PF	PF	WK	LF
151	PF	PF	HF	WK
152	PF	PF	HF	HF
153	PF	PF	HF	PF
154	PF	PF	HF	LF
155	PF	PF	PF	WK
156	PF	PF	PF	HF
157	PF	PF	PF	PF
158	PF	PF	PF	LF
159	PF	PF	LF	WK
160	PF	PF	LF	HF
161	PF	PF	LF	PF
162	PF	LF	WK	WK
163	PF	LF	WK	HF
164	PF	LF	WK	PF
165	PF	LF	WK	LF
166	PF	LF	HF	WK
167	PF	LF	HF	HF
168	PF	LF	HF	PF
169	PF	LF	HF	LF
170	PF	LF	PF	WK
171	PF	LF	PF	HF
172	PF	LF	PF	PF
173	PF	LF	PF	LF
174	PF	LF	LF	WK
175	PF	LF	LF	HF
176	PF	LF	LF	PF
177	PF	LF	LF	LF
178	LF	WK	WK	WK
179	LF	WK	WK	HF
180	LF	WK	WK	PF
181	LF	WK	WK	LF
182	LF	WK	HF	WK
183	LF	WK	HF	HF
184	LF	WK	HF	PF
185	LF	WK	HF	LF
186	LF	WK	PF	WK
187	LF	WK	PF	HF
188	LF	WK	PF	PF
189	LF	WK	PF	LF
190	LF	WK	LF	WK
191	LF	WK	LF	HF
192	LF	WK	LF	PF
193	LF	WK	LF	LF
194	LF	HF	WK	WK
195	LF	HF	WK	HF
196	LF	HF	WK	PF
197	LF	HF	WK	LF
198	LF	HF	HF	WK
199	LF	HF	HF	HF
200	LF	HF	HF	PF
201	LF	HF	HF	LF
202	LF	HF	PF	WK
203	LF	HF	PF	HF
204	LF	HF	LF	WK
205	LF	HF	LF	HF
206	LF	PF	WK	WK
207	LF	PF	WK	HF
208	LF	PF	WK	PF
209	LF	PF	WK	LF
210	LF	PF	HF	WK
211	LF	PF	HF	HF
212	LF	PF	HF	PF
213	LF	PF	HF	LF
214	LF	PF	PF	WK

Table 8.12: Nimrod fuel system tank 5 sub-section scenarios - 2

Scenario	FT0201	FT0205	FT0215	FT0225	Scenario	FT0201	FT0205	FT0215	FT0225
215	LF	PF	PF	HF	226	LF	LF	HF	HF
216	LF	PF	PF	PF	227	LF	LF	HF	PF
217	LF	PF	PF	LF	228	LF	LF	HF	LF
218	LF	PF	LF	WK	229	LF	LF	PF	WK
219	LF	PF	LF	HF	230	LF	LF	PF	HF
220	LF	PF	LF	PF	231	LF	LF	PF	PF
221	LF	LF	WK	WK	232	LF	LF	PF	LF
222	LF	LF	WK	HF	233	LF	LF	LF	WK
223	LF	LF	WK	PF	234	LF	LF	LF	HF
224	LF	LF	WK	LF	235	LF	LF	LF	PF
225	LF	LF	HF	WK	236	LF	LF	LF	LF

Table 8.13: Nimrod fuel system tank 5 sub-section scenarios - 3

There are 20 invalid scenarios, shown in Table 8.14.

Scenario	FT0201	FT0205	FT0215	FT0225	Scenario	FT0201	FT0205	FT0215	FT0225
1	WK	HF	PF	PF	11	PF	HF	PF	PF
2	WK	HF	PF	LF	12	PF	HF	PF	LF
3	WK	HF	LF	PF	13	PF	HF	LF	LF
4	WK	HF	LF	LF	14	PF	HF	LF	WK
5	WK	PF	LF	LF	15	PF	PF	LF	LF
6	HF	HF	PF	PF	16	LF	HF	PF	PF
7	HF	HF	PF	LF	17	LF	HF	PF	LF
8	HF	HF	LF	LF	18	LF	HF	LF	LF
9	HF	HF	LF	WK	19	LF	HF	LF	WK
10	HF	PF	LF	LF	20	LF	PF	LF	LF

Table 8.14: Nimrod fuel system tank 5 invalid sub-section scenarios

Scenarios 1 to 4, 6 to 9, 11 to 14 and 16 to 19 cannot occur because high flow cannot occur at FT0205 if there is only partial or no flow at FT0215 or FT0225. Scenarios 5, 10, 15 and 20 cannot occur because low flow at FT0215 and FT0225 will not result in partial flow at FT0205.

Patterns

In the same way as for the key variables a set of patterns can be developed from the flow rate and level measurement history for the sensors in the fuselage section, as shown in Table 8.15 using the scenarios in Table 8.8.

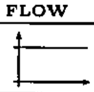
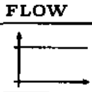
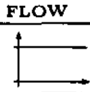
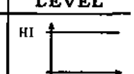
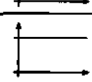
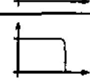
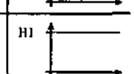
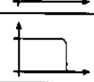
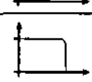
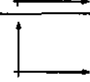
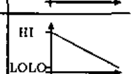
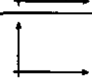
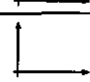
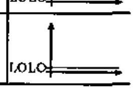
	Scenarios	FT0200 FLOW	FT0300 FLOW	FT0201 FLOW	LT0201 LEVEL
XFERFuselagePhase1	1, 2, 5, 6, 17, 18, 21, 22				
XFERFuselagePhase2	1, 2, 5, 6, 17, 18, 21, 22				
XFERFuselagePhase3	1, 4, 5, 8, 17, 20, 21, 24				
XFERFuselagePhase4	1, 4, 13, 16, 49, 52, 61, 64				

Table 8.15: Expected sensor patterns for the fuselage section in the XFER operating mode - 1

The patterns from the fuselage section will indicate the scenarios which the system could potentially be in and highlight the area or areas in which a problem has occurred. The reading at FT0201 into collecting tank 1 can indicate if there is a problem with fuel flow into this tank from the feeding tanks. Patterns can be developed for the sensor readings FT0201, FT0211 and FT0205 used to develop the scenarios introduced in Table 8.9. Expected pattern behaviour is shown in Table 8.16.

	Scenarios	FT0201 FLOW	LT0201 LEVEL	FT0211 FLOW	FT0205 FLOW	LT0205 LEVEL
XFERFuselageCollectorPhase1	1, 4, 5, 8, 17, 20, 21, 24		HI			HI
XFERFuselageCollectorPhase2	1, 2, 5, 6, 17, 18, 21, 22		HI			HI LOLO
XFERFuselageCollectorPhase3	1, 4, 13, 16, 49, 52, 61, 64		HI LOLO			LOLO
XFERFuselageCollectorPhase4	1, 4, 13, 16, 49, 52, 61, 64		LOLO			LOLO

Table 8.16: Expected sensor patterns for the fuselage section in the XFER operating mode - 2

Deviation from these expected patterns will indicate whether a failure has occurred in tank 5 or from tanks 6, 7R or 7L, which are linked to the collecting tank by the same line. A set of expected patterns for the sub-sections containing tanks 6, 7R and 7L along with their potential scenarios introduced in Table 8.10 are shown in Table 8.17.

	Scenarios	FT0201 FLOW	FT0211 FLOW	FT0206 FLOW	LT0206 LEVEL	LT0207R FLOW	FT0207L FLOW	LT0207L LEVEL
XFER67LRPhase1	1, 2, 5, 6, 17, 18, 21, 22, 65, 66, 69, 70, 81, 82, 85, 86				HI	HI LOLO		HI LOLO
XFER67LRPhase2	1, 4, 5, 8, 17, 20, 21, 24, 65, 68, 69, 72, 81, 84, 85, 88				HI LOLO	LOLO		LOLO
XFER67LRPhase3	1, 4, 13, 16, 17, 20, 29, 32, 65, 68, 77, 80, 81, 84, 93, 96				LOLO	LOLO		LOLO
XFER67LRPhase4	1, 4, 13, 16, 49, 52, 61, 64, 193, 196, 205, 208, 241, 244, 253, 256				LOLO	LOLO		LOLO

Table 8.17: Expected sensor patterns for the fuselage section in the XFER operating mode - 3

The tank or tanks in the section in which there is a problem in the fuselage can be indicated from the patterns for FT0201, FT0205, FT0215 and FT0225 (see Table 8.16). A deviation at FT0205 will indicate a problem in tank 5 in the system. This can then be investigated in order to focus in on the possible problem area and determine the possible cause. The patterns and their potential scenarios are shown in Table 8.18.

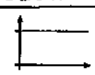
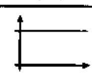
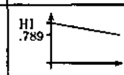
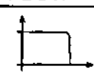
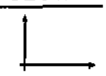
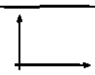
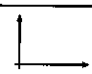
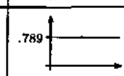
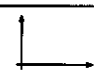
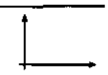
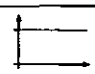
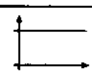
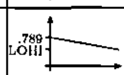
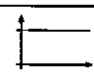
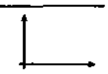
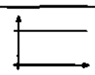
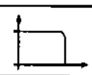
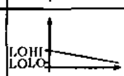
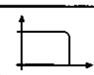
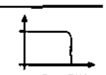
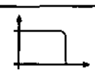
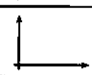
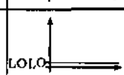
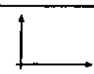
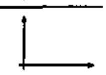
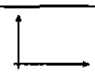
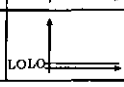
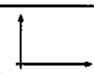
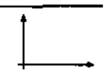
	Scenarios	FT0201 FLOW	FT0205 FLOW	LT0205L LEVEL	FT0215 FLOW	FT0225 FLOW
XFERFuselageTank5Phase1	1, 4, 5, 8, 17, 20, 21, 24, 65, 68, 69, 72, 81, 84, 85, 88					
XFERFuselageTank5Phase2	1, 4, 13, 16, 49, 52, 61, 64, 193, 196, 205, 208, 241, 244, 253, 256					
XFERFuselageTank5Phase3	1, 4, 5, 8, 17, 20, 21, 24, 65, 68, 69, 72, 81, 84, 85, 88					
XFERFuselageTank5Phase4	1, 2, 5, 6, 17, 18, 21, 22, 65, 66, 69, 70, 81, 82, 85, 86					
XFERFuselageTank5Phase5	1, 4, 13, 16, 49, 52, 61, 64, 65, 68, 77, 80, 113, 116, 125, 128					
XFERFuselageTank5Phase6	1, 4, 13, 16, 49, 52, 61, 64, 193, 196, 205, 208, 241, 244, 253, 256					

Table 8.18: Expected sensor patterns for tank 5 in a fuselage section in the XFER operating mode

A fault tree can be constructed from for any patterns that deviate from those expected in a given phase in order to ascertain the most likely causes of failure in the system.

8.2.2.7 Fault Tree Construction

Non-coherent fault trees would be drawn to determine the causality of any deviations from expected behaviour identified from the sensor readings within the system. A tree is developed for each reading that exhibits unexpected behaviour and takes into consideration the operating mode that the system is in along with the potential causes of failure for that given section of the system, thus restricting the boundary of possible causes to the identified area. Success trees are also to remove potential causes that conflict with working parts of the system.

8.3 Discussion

The application of the modelling and preparation stage steps to a real aircraft system has shown that the method could potentially be utilised on larger systems. In order to fully conclude this the application stage steps would also need to be applied. In applying the method to a larger system it has been noted that fuel systems could have an increased number of and more complex operating modes, which will have to be taken into consideration in developing the fault trees and within the application stage of the analysis. It is also important that any assumptions made about the system should be listed.

The Nimrod is a characteristic example of a fuel system and has shown that an increased number of fuel tanks will be more complex to analyse compared to the water tank and fuel rig systems. Investigations into the Nimrod and other fuel systems (Typhoon and Hawk) has indicated that typically fuel is fed from a series of tanks to a collecting tank or engine feed line in order to then be transported to the given engine. A fuel system would require sectioning that enables the possibility of groups of tanks to be analysed rather than the system as a whole. This can be identified depending how the fluid leads into a collecting tank, several collecting tanks or an engine feed line. Analysis can then focus on an individual section and sub-sections within that section rather than the system as a whole, which will aid fault localisation.

In most cases it would be too complex to consider all sensors in a section at the same time because of the number of potential scenarios created and the possible patterns for each. A sensor increases the number of possible scenarios by a multiple of its number of possible failure modes. Each section would contain key variables, these being namely the level within a collecting tank and any sensor monitoring flow into an engine. The key variables enable all sections in the system to be initially analysed as this is enough to indicate a problem somewhere within the system. Conclusions can then be drawn as to which area of the system a failure has occurred depending on the findings. The sections identified as potentially having a problem can then be investigated further. For larger examples sections can be divided into sub-sections. As before the sub-section or sub-sections in which a failure has occurred can then be identified and these be investigated further. This allows the fault to become more and more localised until the area is known and the potential causes of failure obtained.

8.4 Summary

- The modelling and preparation stage steps listed in Section 7.2.1 have been applied to the Nimrod fuel system. This application has indicated that the method does have potential for use on real aircraft fuel systems.

- Within fuel systems fuel is typically fed from a series of tanks to a collecting tank or engine feed line in order to then be transported to the given engine.
- Sectioning is required that enables the possibility of groups of tanks to be analysed rather than the system as a whole. This can be identified depending on how the fluid leads into a collecting tank, several collecting tanks or an engine feed line.
- The identification of key variables enables all sections in the system to be initially analysed as this is enough to indicate a problem somewhere within the system. The area or areas in which a failure has occurred can then be located and investigated further.
- Fuel systems could have an increased number of and more complex operating modes, which will have to be taken into consideration in developing the fault trees and within the application stage of the analysis.

Chapter 9

Conclusions and Future Work

9.1 Introduction

The aim of the research was to develop a method that could be potentially used for diagnosing faults in aircraft fuel systems. The main aspects in the formation of the fault diagnostic method are described in this chapter.

9.2 Summary and Conclusions

9.2.1 Review of Existing Literature

A number of existing fault diagnostic techniques were reviewed in which the failings of currently available methods were identified. The development of a model-based approach was decided upon as it enabled the use of a physical system to determine actual behaviour and to identify all possible states that it could be in at any point in time. System failures are not always the result of one single fault, therefore the ability to diagnose multiple faults is vitally important. The technique employs knowledge of the overall system to find any deviations and can be easily and efficiently developed from this information.

It was concluded that FTA would be utilised to describe all possible causes of a specified system state in terms of the components within the system. The causes of the system's failure modes could then be described in terms of the component states. It was thought that multiple failures could be considered using the fault trees and successful component behaviour through the use of NOT logic to remove any conflicting causes.

9.2.2 FTA for Fault Detection

A method was developed using FTA to diagnose faults in systems. This initially considered aspects of system performance observed at steady-state or specified points in time. The initial work in developing a fault diagnostic method using FTA indicated this technique can be used to identify multiple faults in a systems fault diagnostic capability, as illustrated through the water tank level control system example. The use of non-coherent fault trees to represent the causes of sensor outputs provided more reliable results than those obtained using coherent fault trees.

The introduction of consistency checks with information provided by all sensors is required to produce a more accurate list of potential causes of the current system state. Scheme 4 (II) was found to be the most accurate of the four schemes investigated. The work carried out on the water tank system indicated a number of issues to be considered when developing the method. These were the need for a consistency check within the analysis alongside the issue of scalability and complexity, the possible presence of imperfect or unreliable sensors, the ability of the method to obtain the exact failure cause, dynamic effects and finally the possibility of having more than two system phases.

9.2.3 FTA for Fault Detection When Considering Dynamics

The method was extended to consider system dynamics. This was developed to identify component failures on the water tank system and takes into account the system dynamics using a simple pattern recognition technique. In the majority of cases the method was able to correctly identify the possible potential causes of failure for both the ACTIVE and DORMANT operating modes and this is reflected in the results. The use of fault trees that are restricted to the control systems on each stream has reduced the complexity of the approach and should enable the method to be scaled up on larger systems. The analysis needed to take into consideration the level of water in the tank as this is the key variable within the system and provides important dynamic information.

9.2.4 Expansion to a Larger System

The established method was applied to the BAE Systems fuel rig to investigate the scalability for use on a larger system. The method has been successfully utilised on the fuel rig system, for which system redundancy has also been taken into consideration. In most cases the method has identified the correct potential causes of failure for the given set of sensor patterns. To determine whether the method would be feasible for use on a real aircraft system it was concluded that further application of the approach would be required.

9.2.5 Prospective Expansion to an Aircraft Fuel System

The implications of expanding the method to a full aircraft fuel system were determined. Typical characteristics of a fuel system were identified and how the method could be potentially utilised on a larger system was investigated by considering the application to the Nimrod fuel system. The implications of applying the fault diagnostic method to this system on the current modelling and preparation stage steps in Section 7.2.1 have been identified. It was concluded that the method does have potential for use on real aircraft systems. In order to fully conclude whether the method would be feasible the application stage steps also need to be applied.

9.3 Future Work

The research within this thesis has highlighted a number of areas in which further investigation could potentially be carried out. These areas are now discussed in the following sections.

9.3.1 Binary Decision Diagrams

Fault trees are an effective way of visually representing the failure logic of a system. However, the larger fault trees within the analysis become the greater the complexity of obtaining a solution. This is reduced using approximations in the analysis, but in doing so this leads to a loss of accuracy in the results obtained. An alternative approach would be to convert the fault trees in the diagnostic method to Binary Decision Diagrams (BBDs), developed by Rauzy [83–85], to provide a more efficient way of performing FTA. The method has the potential to exploit the efficiency of BDDs to manipulate the resulting fault trees and produce a set of possible symptom causes that are consistent with all the evidence. This should be investigated as may provide an improvement to the analysis and reduce the complexity encountered when using fault trees.

9.3.2 Laboratory Demonstration

It is possible to link the approach developed to the fuel rig and give a laboratory based demonstration of the method. Whilst this work is in preparation for the practical demonstration it is beyond the scope of the material in this thesis.

9.3.3 Real-Scale System

At present the method has been fully applied to two systems, both of which are relatively small in comparison to a real aircraft fuel system. Application of the method to an aircraft system is therefore required to indicate if it is feasible to use it on larger systems. In order to test the method the example or examples that it is applied to should contain one or more of the following features:

- An increase in the complexity of system sectioning,
- An increase in the number of system sensors,
- Different modes of operation considered (other than engine feed (ACTIVE) or engine shut down (DORMANT)).

The modelling and preparation stage steps for the Nimrod fuel system have already been conducted and shows that this contains all these additional features.

9.3.4 Sensor Reliability

So far it has been assumed that the sensors that give the system variables in the method are reliable. Failures in these sensors have been noted to be identifiable when conflicting readings occur as these are highlighted through the patterns obtained. Further investigation is required to identify failures in sensors that show the system performing a certain task with no conflicting readings, but the system is actually functioning in a different way. For instance, flow is indicated on an outflow line in a tank when there is no flow at this point, or if a tank level is constant, but flow is occurring out of it.

9.3.5 Hidden Symptoms

The method is not able to identify any hidden failures of components that have the same symptoms as when they are working as required. This is a restriction in the analysis that at present cannot be resolved unless either a change of operating mode is made that alters the expected system behaviour such that a failure is indicated, or the area of the system in which a hidden failure is located is used. The method could be extended to produce a list of hidden failures that could have potentially occurred for the given system status. For instance, for the water tank system if valve V2 is open as expected then a potential hidden failure could be V2FO. These could be potentially identified through the system scenarios in the method. The scenario indicating the most deviated sensor readings could be used to identify an outcome that includes the possible hidden failures present within the system. Alternatively a set of scenarios could be developed from the sensor patterns identified.

9.3.6 Dynamics

The most likely scenario to have caused a deviation is that which contains the least number of deviated sensor readings. However, without scenarios in the method there would be no proper structure in the identification of patterns exhibited by the sensor readings. Further work could involve identifying all possible patterns for each sensor or groups of sensors within the system and how these would impact on the behaviour. Rather than using all the possible scenarios in the analysis the one causing the least sensor deviations could be indicated and used to identify the system status. This could potentially reduce the complexity of the fault tree produced in the analysis. The method may benefit from having the ability to distinguish in more detail the patterns with the scenarios, but this may lead to a more complex set of scenarios as a result of more possible outcomes for each sensor.

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Appendix A

Fault Trees for the Water Tank Level Control System

A.1 Coherent Fault Trees

A.1.1 Flow Through Valve V1

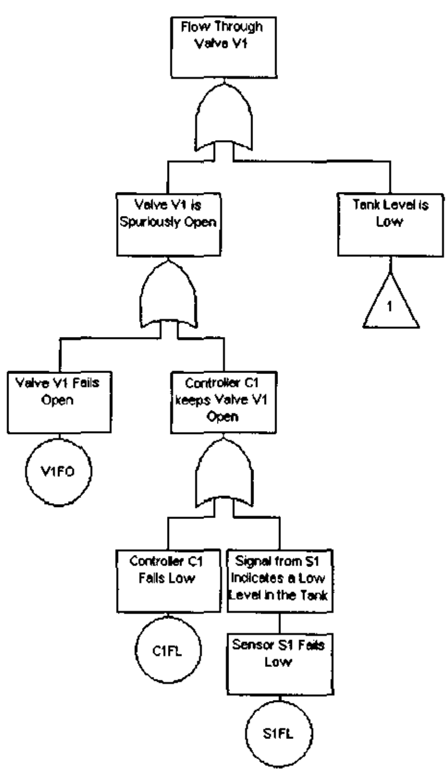


Figure A.1: Coherent fault tree for flow through valve V1

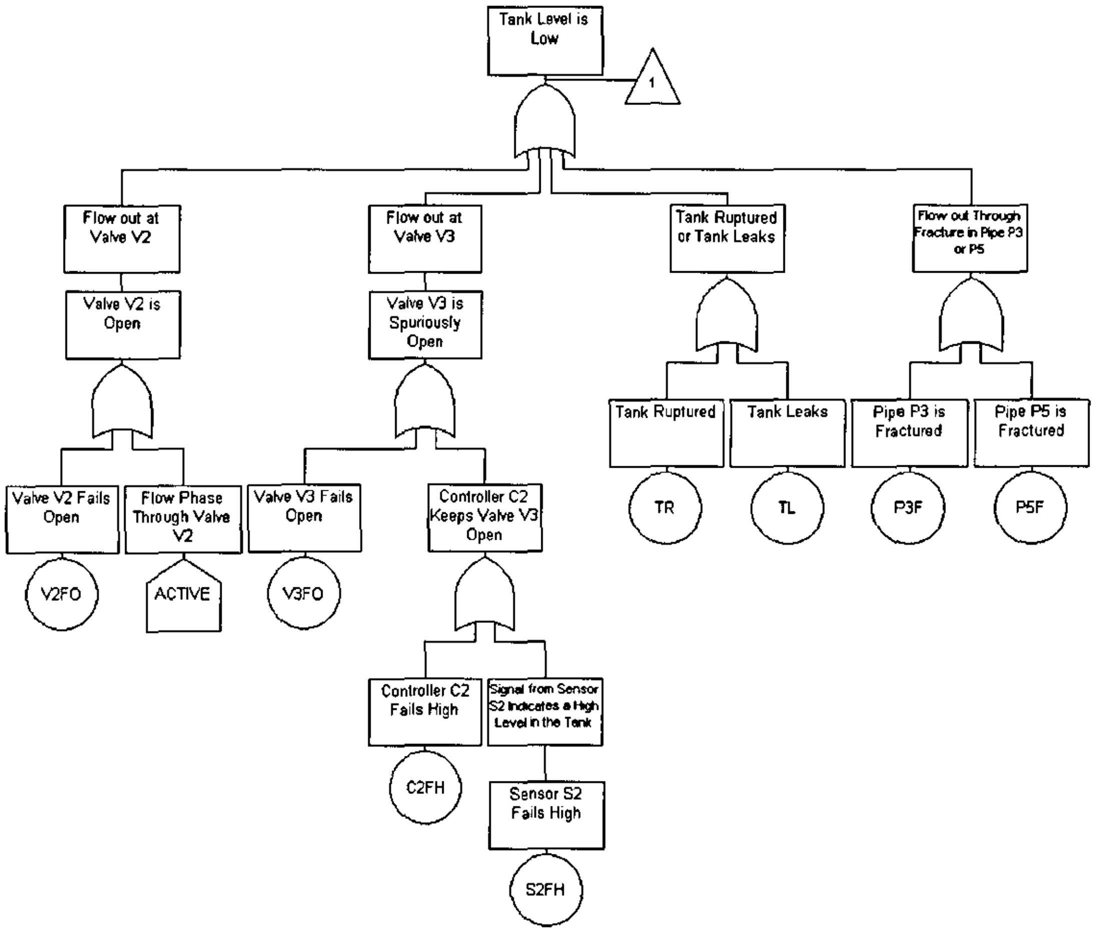


Figure A.2: Coherent fault tree for flow through valve V1 - transfer 1

Number	Potential Cause
1)	V1FO
2)	C1FL
3)	S1FL
4)	TL
5)	TR
6)	V2FO

Number	Potential Cause
7)	P3F
8)	V3FO
9)	C2FH
10)	S2FH
11)	P5F

Table A.1: Potential causes of flow through valve V1

A.1.2 Flow Through Valve V2

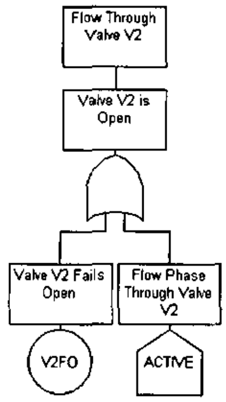


Figure A.3: Coherent fault tree for flow through valve V2

The only possible potential cause of system failure for this sensor reading is V2FO, which is of first order.

A.1.3 Flow Through Valve V3

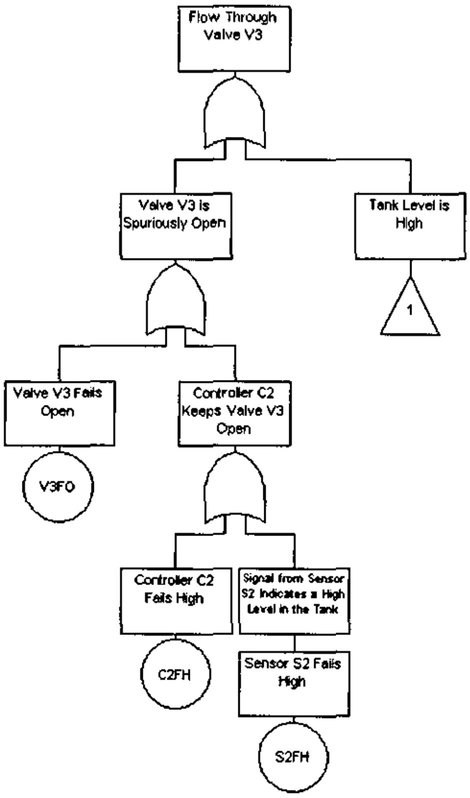


Figure A.4: Coherent fault tree for flow through valve V3

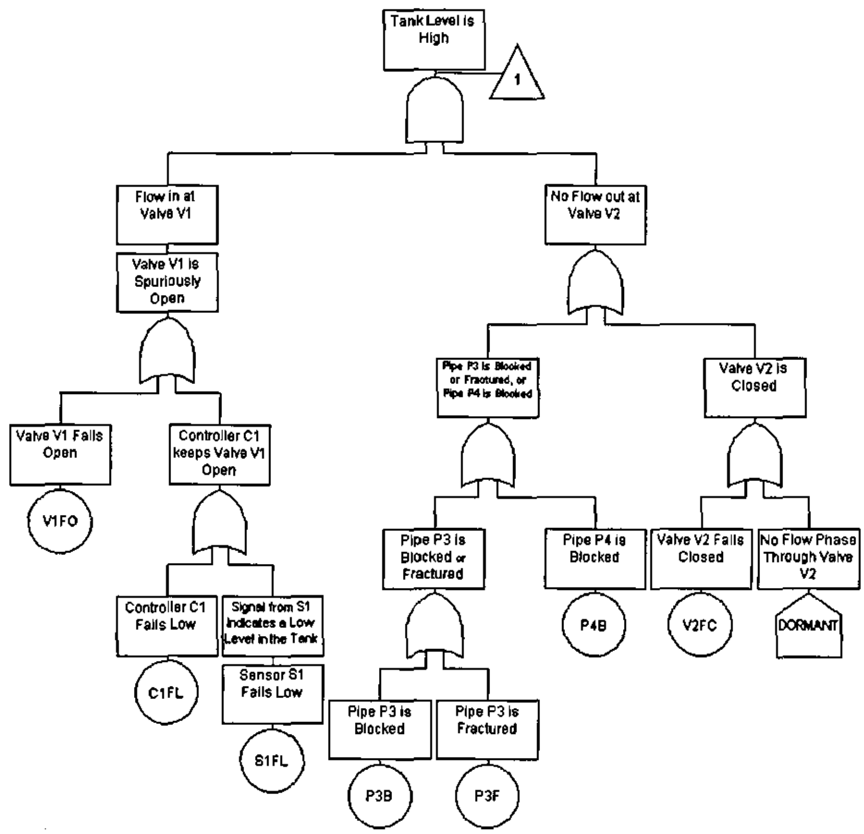


Figure A.5: Coherent fault tree for flow through valve V3 - transfer 1

Number	Potential Cause
1)	V3FO
2)	C2FH
3)	S2FH
4)	V1FO.P3B
5)	V1FO.P3F
6)	V1FO.P4B
7)	V1FO.V2FC
8)	C1FL.P3B
9)	C1FL.P3F
10)	C1FL.P4B
11)	C1FL.V2FC
12)	S1FL.P3B
13)	S1FL.P3F
14)	S1FL.P4B
15)	S1FL.V2FC

Table A.2: Potential causes of flow through valve V3 when the system is ACTIVE

Number	Potential Cause
1)	V3FO
2)	C2FH
3)	S2FH
4)	V1FO
5)	C1FL
6)	S1FL

Table A.3: Potential causes of flow through valve V3 when the system is DORMANT

A.1.4 No Flow Through Valve V1

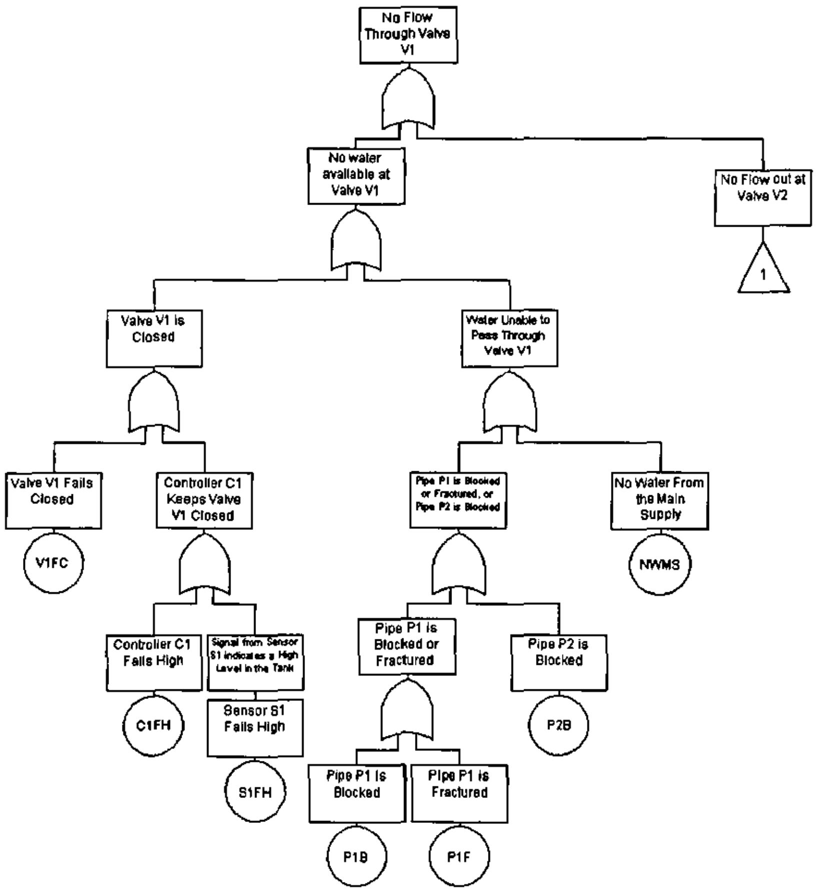


Figure A.6: Coherent fault tree for no flow through valve V1

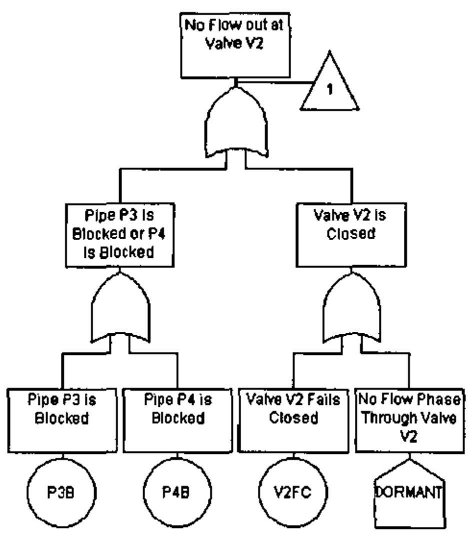


Figure A.7: Coherent fault tree for no flow through valve V1 - transfer 1

Number	Potential Cause	Number	Potential Cause
1)	V1FC	6)	P2B
2)	C1FH	7)	NWMS
3)	S1FH	8)	V2FC
4)	P1B	9)	P3B
5)	P1F	10)	P4B

Table A.4: Potential causes of no flow through valve V1

A.1.5 Water in the Overspill Tray

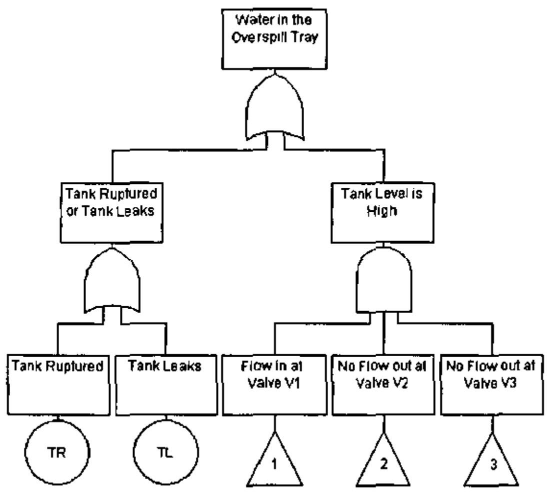


Figure A.8: Coherent fault tree for water in the overspill tray

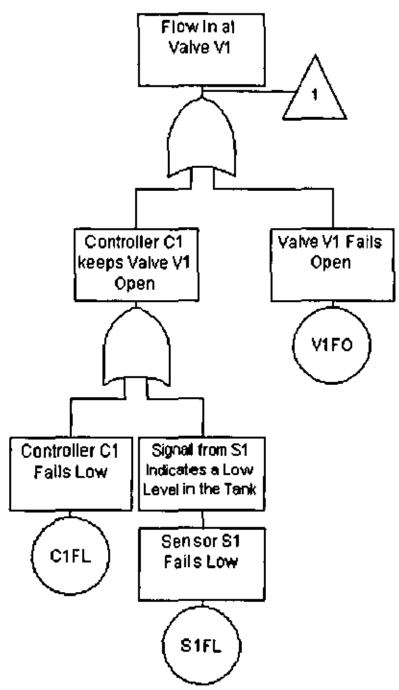


Figure A.9: Coherent fault tree for water in the overspill tray - transfer 1

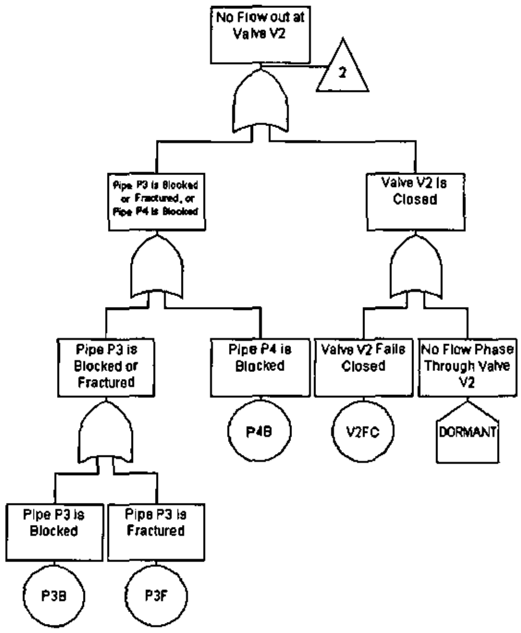


Figure A.10: Coherent fault tree for water in the overspill tray - transfer 2

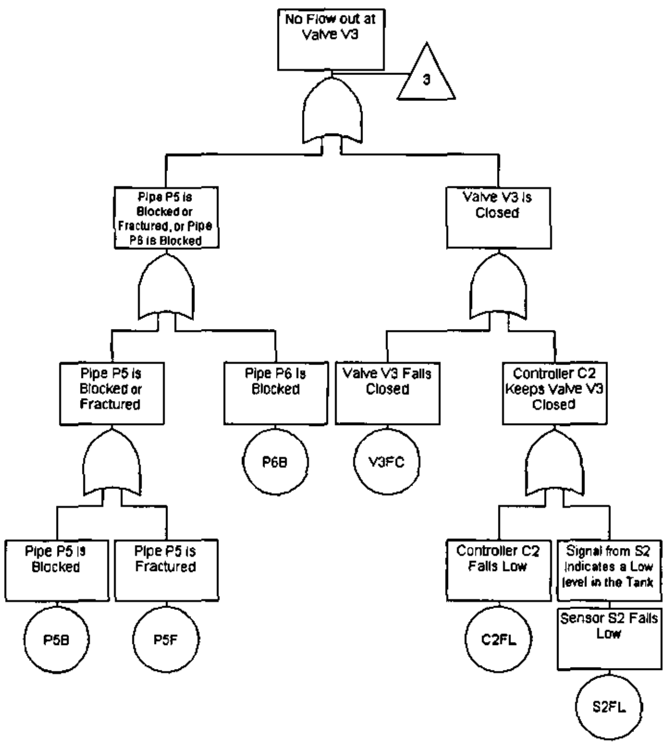


Figure A.11: Coherent fault tree for water in the overspill tray - transfer 3

Number	Potential Cause
1)	TR
2)	TL
3)	V1FO.V2FC.V3FC
4)	V1FO.V2FC.C2FL
5)	V1FO.V2FC.S2FL
6)	V1FO.V2FC.P5B
7)	V1FO.V2FC.P5F
8)	V1FO.V2FC.P6B
9)	V1FO.P3B.V3FC
10)	V1FO.P3B.C2FL
11)	V1FO.P3B.S2FL
12)	V1FO.P3B.P5B
13)	V1FO.P3B.P5F
14)	V1FO.P3B.P6B
15)	V1FO.P4B.V3FC
16)	V1FO.P3F.C2FL
17)	V1FO.P3F.S2FL
18)	V1FO.P3F.P5B
19)	V1FO.P3F.P5F
20)	V1FO.P3F.P6B
21)	V1FO.P4B.V3FC
22)	V1FO.P4B.C2FL
23)	V1FO.P4B.S2FL
24)	V1FO.P4B.P5B
25)	V1FO.P4B.P5F
26)	V1FO.P4B.P6B
27)	C1FL.V2FC.V3FC
28)	C1FL.V2FC.C2FL
29)	C1FL.V2FC.S2FL
30)	C1FL.V2FC.P5B
31)	C1FL.V2FC.P5F
32)	C1FL.V2FC.P6B
33)	C1FL.P3B.V3FC
34)	C1FL.P3B.C2FL
35)	C1FL.P3B.S2FL
36)	C1FL.P3B.P5B
37)	C1FL.P3B.P5F

Number	Potential Cause
38)	C1FL.P3B.P6B
39)	C1FL.P3F.V3FC
40)	C1FL.P3F.C2FL
41)	C1FL.P3F.S2FL
42)	C1FL.P3F.P5B
43)	C1FL.P3F.P5F
44)	C1FL.P3F.P6B
45)	C1FL.P4B.V3FC
46)	C1FL.P4B.C2FL
47)	C1FL.P4B.S2FL
48)	C1FL.P4B.P5B
49)	C1FL.P4B.P5F
50)	C1FL.P4B.P6B
51)	S1FL.V2FC.V3FC
52)	S1FL.V2FC.C2FL
53)	S1FL.V2FC.S2FL
54)	S1FL.V2FC.P5B
55)	S1FL.V2FC.P5F
56)	S1FL.V2FC.P6B
57)	S1FL.P3B.V3FC
58)	S1FL.P3B.C2FL
59)	S1FL.P3B.S2FL
60)	S1FL.P3B.P5B
61)	S1FL.P3B.P5F
62)	S1FL.P3B.P6B
63)	S1FL.P3F.V3FC
64)	S1FL.P3F.C2FL
65)	S1FL.P3F.S2FL
66)	S1FL.P3F.P5B
67)	S1FL.P3F.P5F
68)	S1FL.P3F.P6B
69)	S1FL.P4B.V3FC
70)	S1FL.P4B.C2FL
71)	S1FL.P4B.S2FL
72)	S1FL.P4B.P5B
73)	S1FL.P4B.P5F
74)	S1FL.P4B.P6B

Table A.5: Potential causes of water in the overspill tray when the system is ACTIVE

Number	Potential Cause
1)	TR
2)	TL
3)	V1FO.V3FC
4)	V1FO.C2FL
5)	V1FO.S2FL
6)	V1FO.P5B
7)	V1FO.P5F
8)	V1FO.P6B
9)	C1FL.V3FC
10)	C1FL.C2FL

Number	Potential Cause
11)	C1FL.S2FL
12)	C1FL.P5B
13)	C1FL.P5F
14)	C1FL.P6B
15)	S1FL.V3FC
16)	S1FL.C2FL
17)	S1FL.S2FL
18)	S1FL.P5B
19)	S1FL.P5F
20)	S1FL.P6B

Table A.6: Potential causes of water in the overspill tray when the system is DORMANT

A.2 Non-Coherent Fault Trees

A.2.1 Flow Through Valve V1

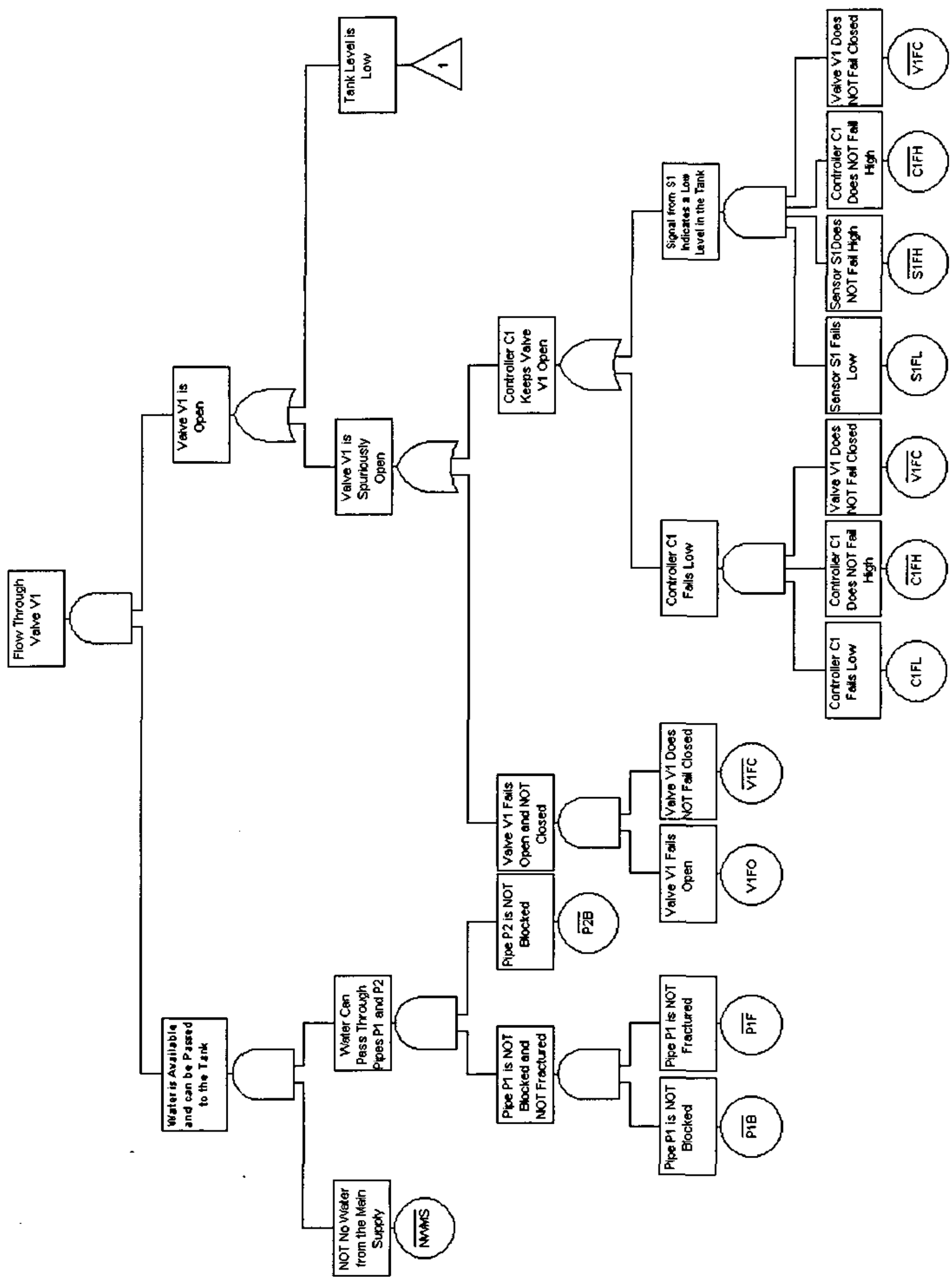


Figure A.12: Non-coherent fault tree for flow through valve V1

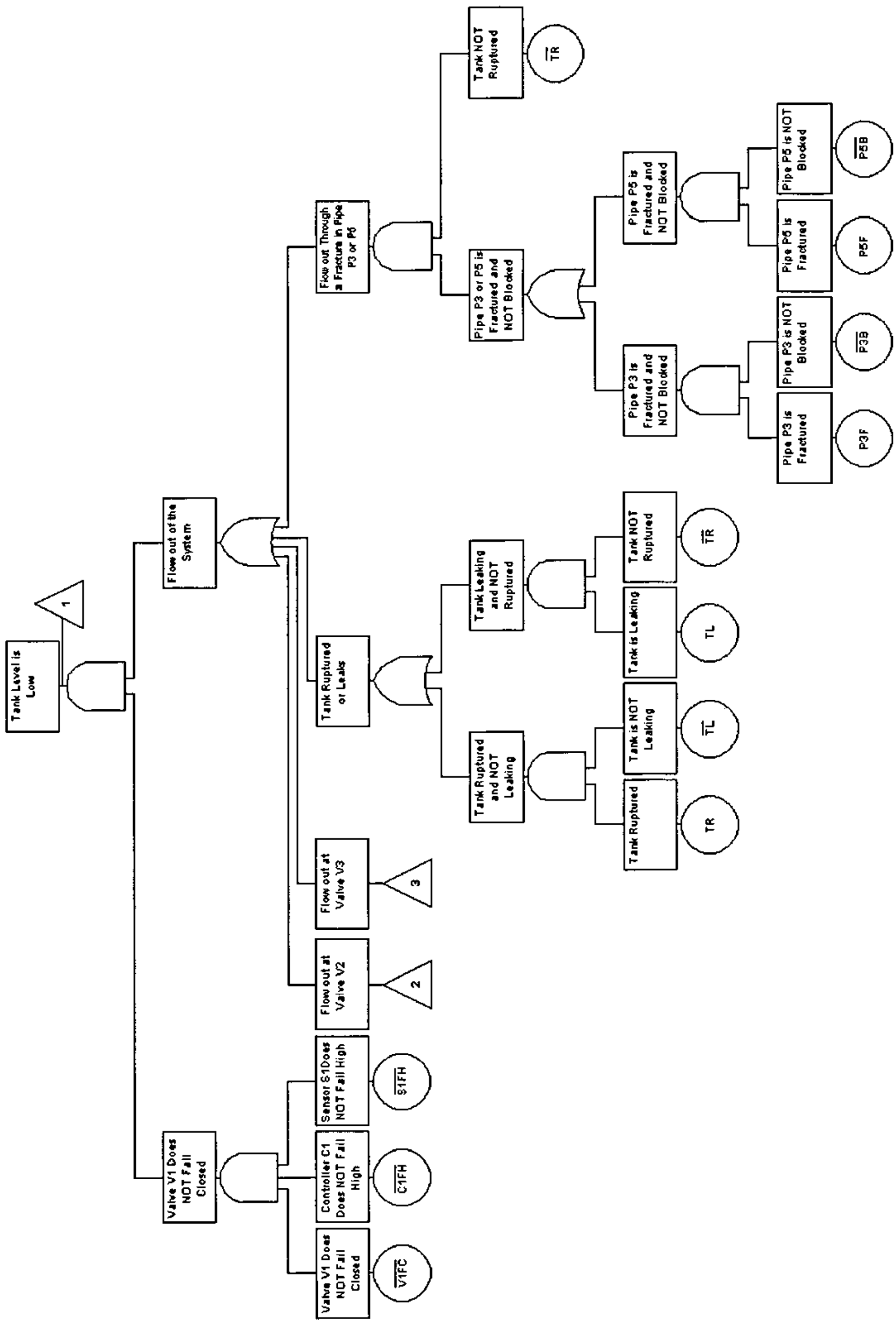


Figure A.13: Non-coherent fault tree for flow through valve V1 - transfer 1

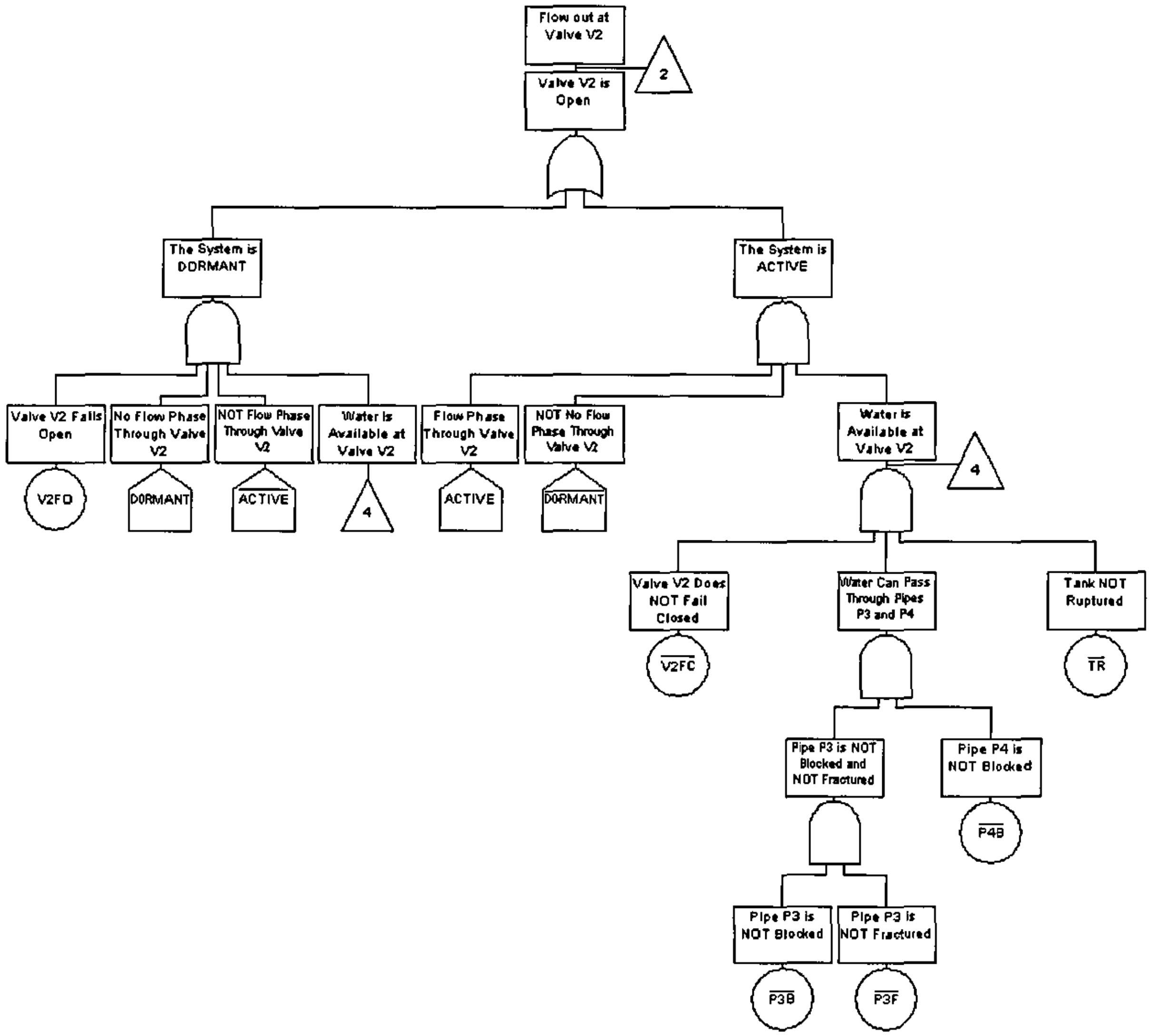


Figure A.14: Non-coherent fault tree for flow through valve V1 - transfer 2

Number	Prime Implicants
1)	$V1FO.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}$
2)	$C1FL.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}$
3)	$S1FL.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}$
4)	$TR.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{TL}$
5)	$TL.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{TR}$
6)	$P3F.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{P3B}.\overline{TR}$
7)	$P5F.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{P5B}.\overline{TR}$
8)	$V2FO.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{V2FC}.\overline{P3B}.\overline{P3F}.\overline{P4B}.\overline{TR}$
9)	$V3FO.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{V3FC}.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{TR}$
10)	$C2FH.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{V3FC}.\overline{C2FH}.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{TR}$
11)	$S2FH.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{V3FC}.\overline{C2FH}.\overline{S2FH}.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{TR}$

Table A.7: Prime implicants for flow through valve V1
when the system is DORMANT

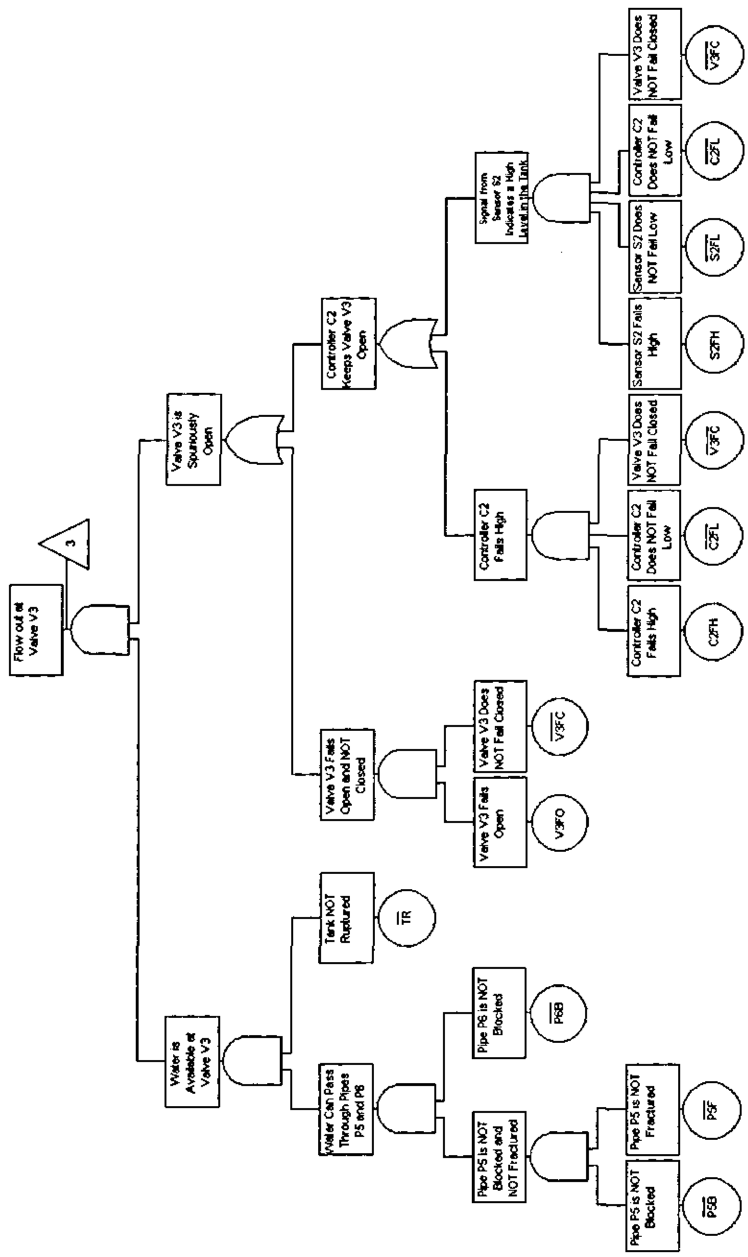


Figure A.15: Non-coherent fault tree for flow through valve V1 - transfer 3

Number	Prime Implicants
1)	NWMS.P1B.P1F.P2B.V1FC.C1FH.S1FH.V2FC.P3B .P4B

Table A.8: Prime implicants for flow through valve V1 when the system is ACTIVE

A.2.2 Flow Through Valve V2

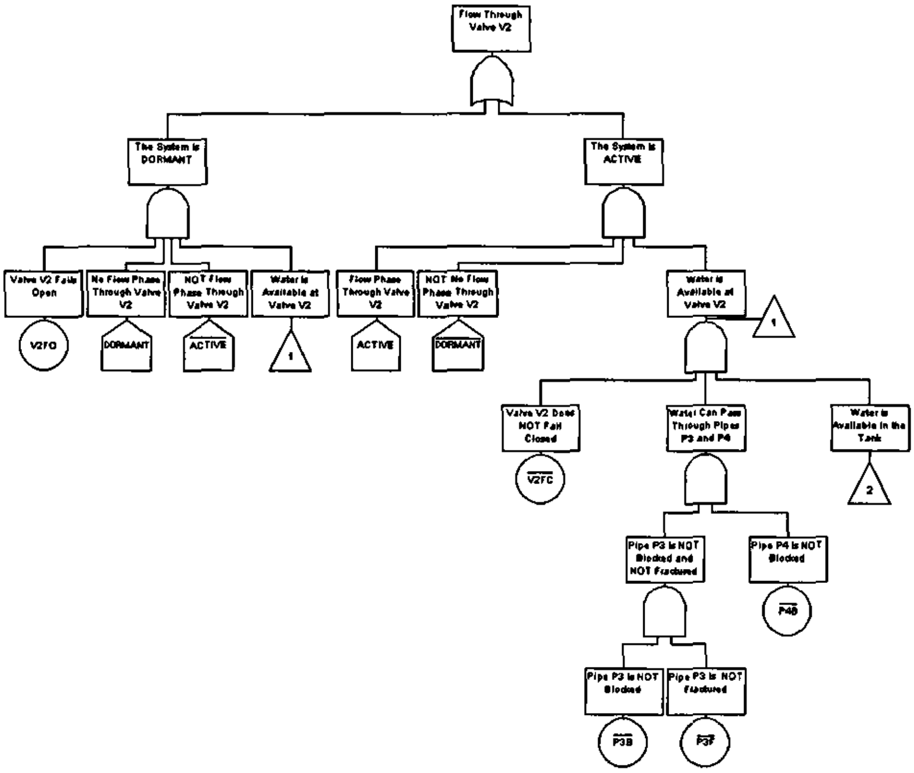


Figure A.16: Non-coherent fault tree for flow through valve V2

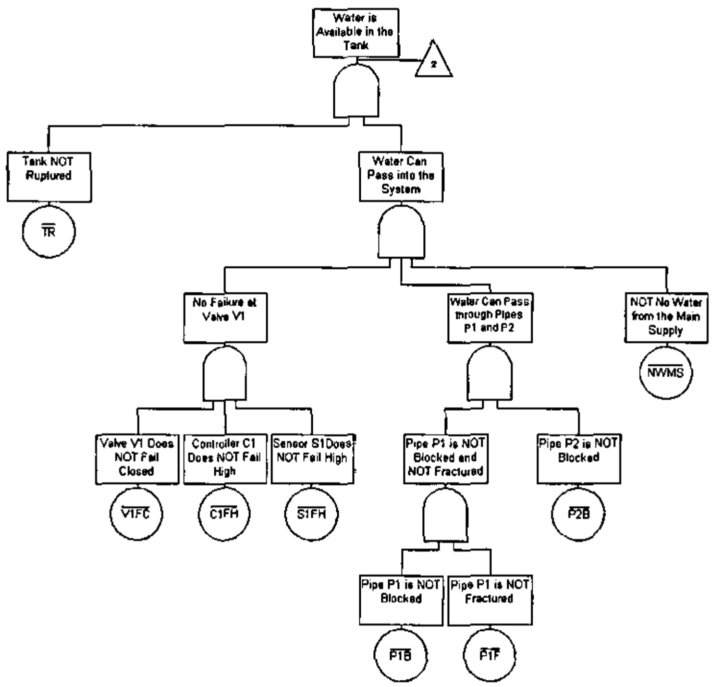


Figure A.17: Non-coherent fault tree for flow through valve V2 - transfer 2

If the system is ACTIVE then flow through valve V2 is expected and so does not result in failure. The prime implicant obtained for this operating mode is:

$$\overline{V2FC}.\overline{P3B}.\overline{P3F}.\overline{P4B}.\overline{TR}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS},$$

This is of order 12 and contains only the components and states that are known NOT to have failed. The prime implicant failure obtained for this sensor reading when the system is DORMANT is:

$$V2FO.\overline{V2FC}.\overline{P3B}.\overline{P3F}.\overline{P4B}.\overline{TR}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS},$$

and is of order 13. After performing the coherent approximation the result obtained for 'flow through valve V2' is 'V2FO', which is the same as that obtained by the coherent fault tree for this reading in Section A.1.2.

A.2.3 Flow Through Valve V3

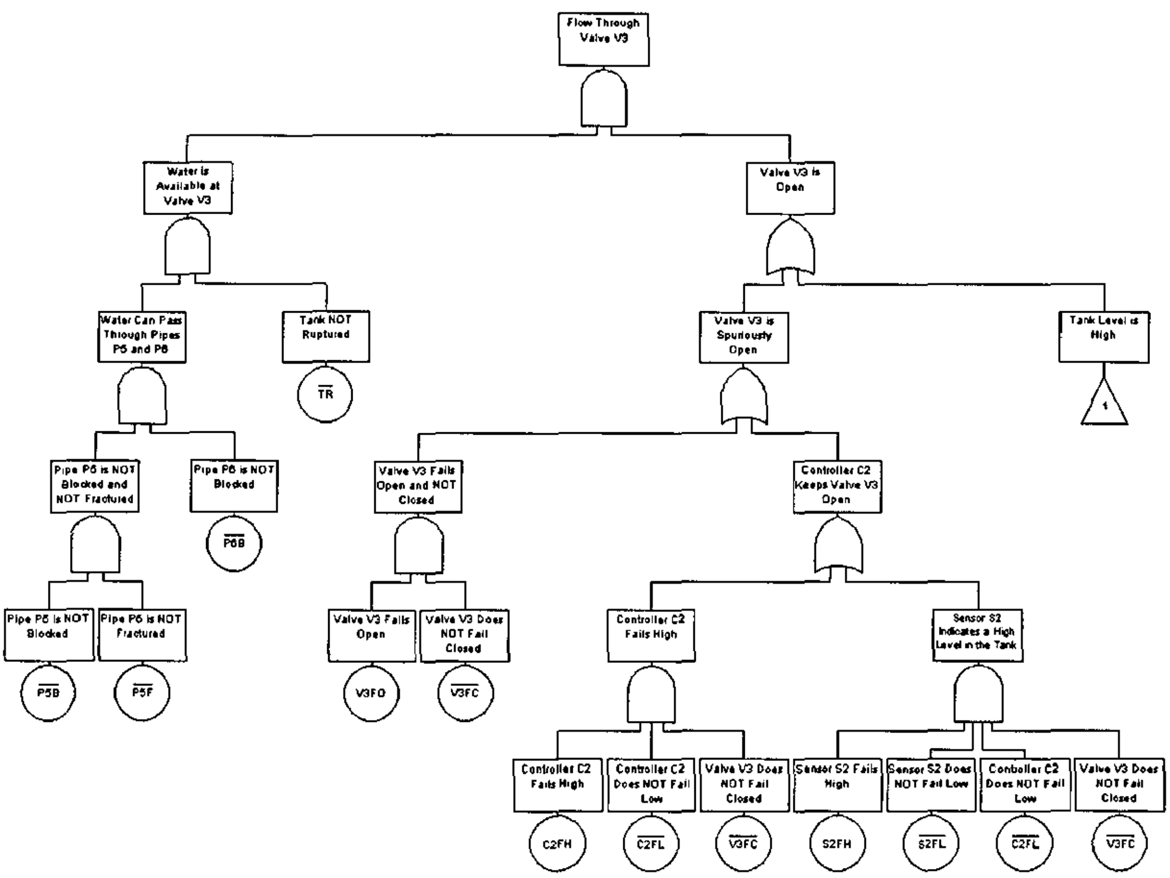


Figure A.18: Non-coherent fault tree for flow through valve V3

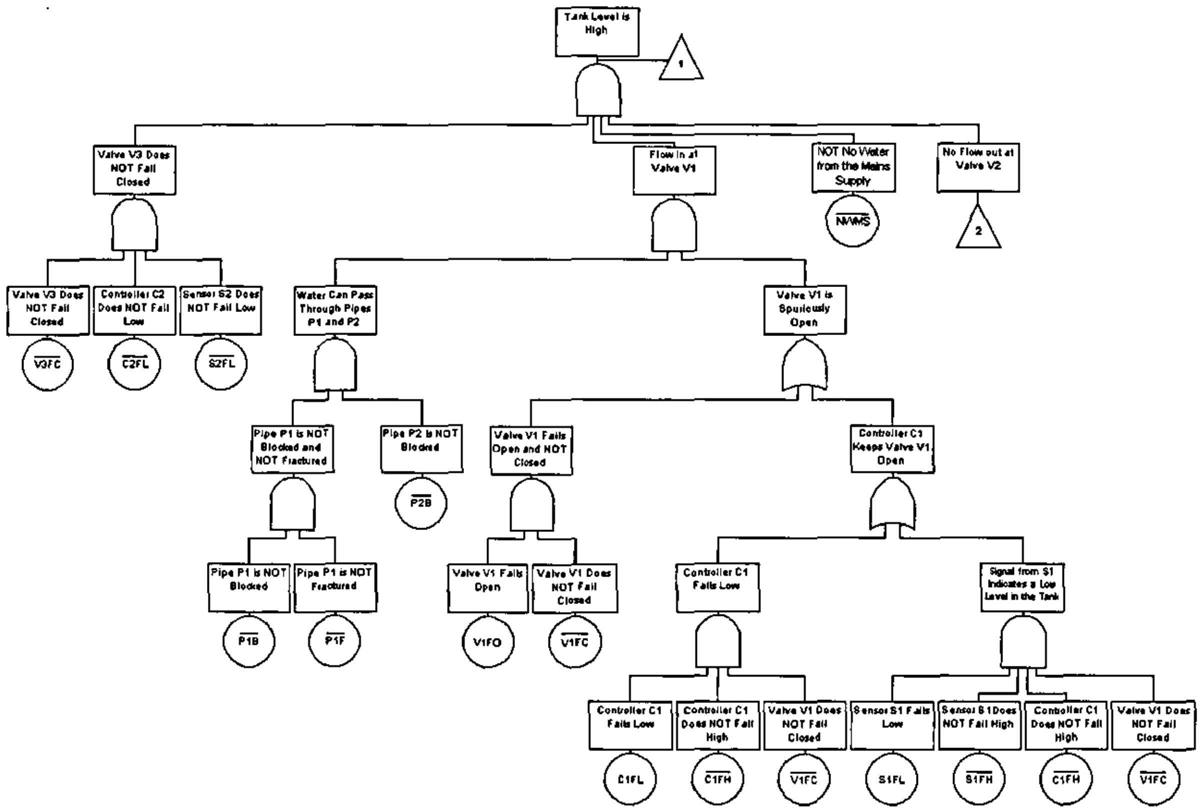


Figure A.19: Non-coherent fault tree for flow through valve V3 - transfer 1

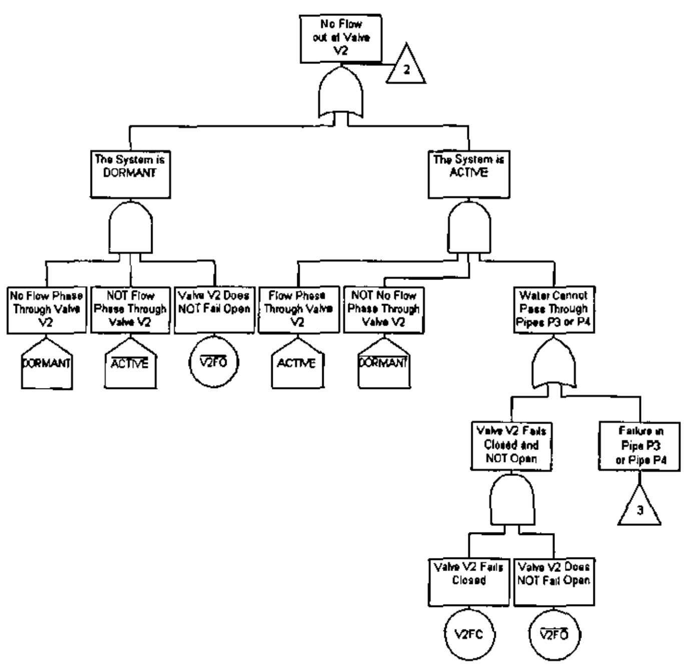


Figure A.20: Non-coherent fault tree for flow through valve V3 - transfer 2

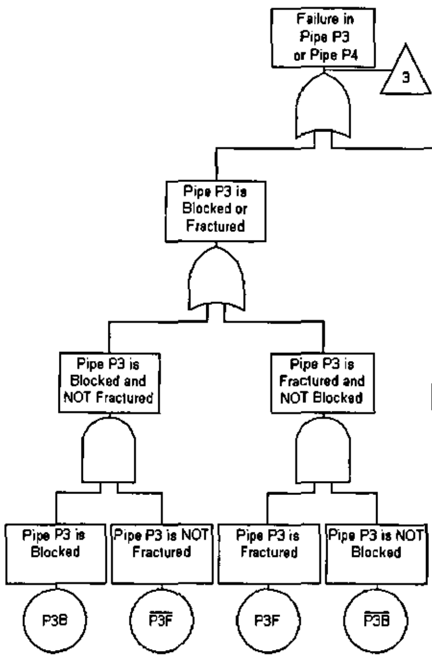


Figure A.21: Non-coherent fault tree for flow through valve V3 - transfer 3

Number	Prime Implicants
1)	$\mathrm{V3FO}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}$
2)	$\mathrm{C2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}$
3)	$\mathrm{S2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}$
4)	$\mathrm{V1FO}.\mathrm{P3B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{P3F}}$
5)	$\mathrm{V1FO}.\mathrm{P3F}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{P3B}}$
6)	$\mathrm{V1FO}.\mathrm{P4B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{P4F}}$
7)	$\mathrm{V1FO}.\mathrm{V2FC}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{V2FO}}$
8)	$\mathrm{C1FL}.\mathrm{P3B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{P3F}}$
9)	$\mathrm{C1FL}.\mathrm{P3F}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{P3B}}$
10)	$\mathrm{C1FL}.\mathrm{P4B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{P4F}}$
11)	$\mathrm{C1FL}.\mathrm{V2FC}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V2FO}}$
12)	$\mathrm{S1FL}.\mathrm{P3B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}$
13)	$\mathrm{S1FL}.\mathrm{P3F}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}$
14)	$\mathrm{S1FL}.\mathrm{P4B}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}$
15)	$\mathrm{S1FL}.\mathrm{V2FC}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}$

Table A.9: Prime implicants for flow through valve V3 when the system is ACTIVE

Number	Prime Implicants
1)	$\mathrm{V3FO}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}$
2)	$\mathrm{C2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}$
3)	$\mathrm{S2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}$
4)	$\mathrm{V1FO}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}$
5)	$\mathrm{C1FL}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}$
6)	$\mathrm{S1FL}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{TR}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}$

Table A.10: Prime implicants for flow through valve V3 when the system is DORMANT

A.2.4 No Flow Through Valve V1

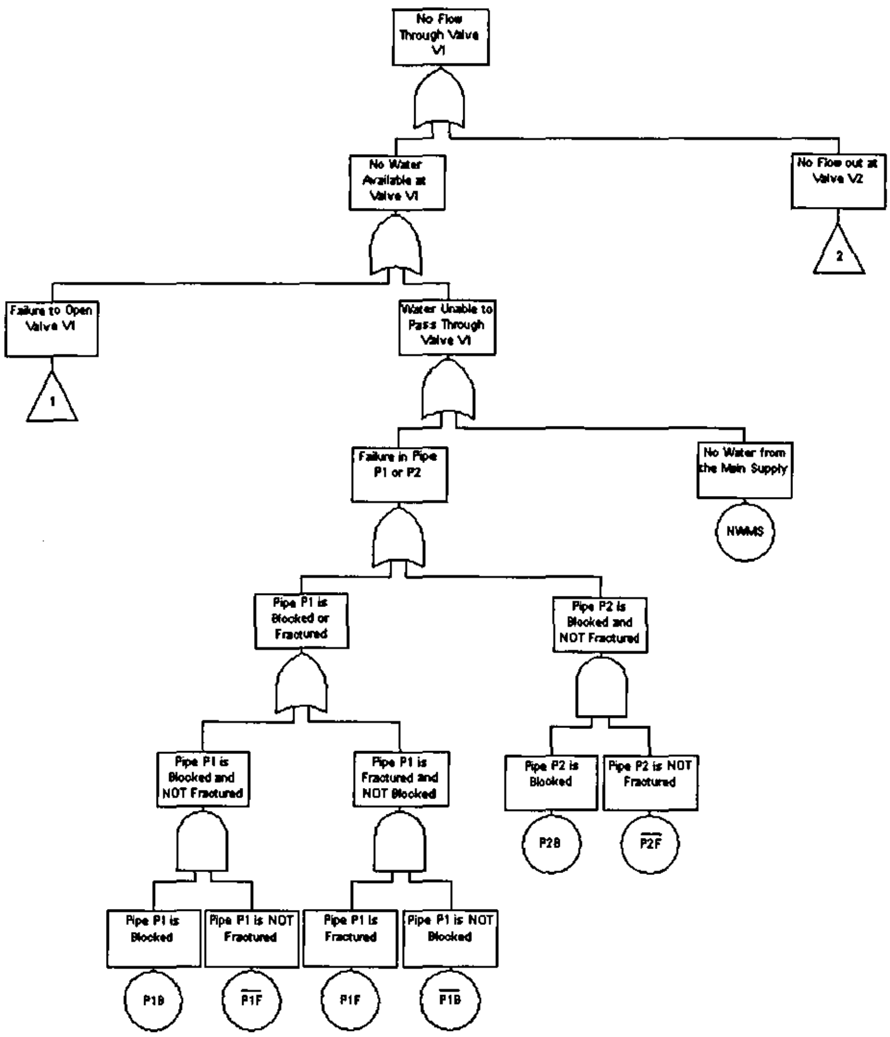


Figure A.22: Non-Coherent fault tree for no flow through valve V1

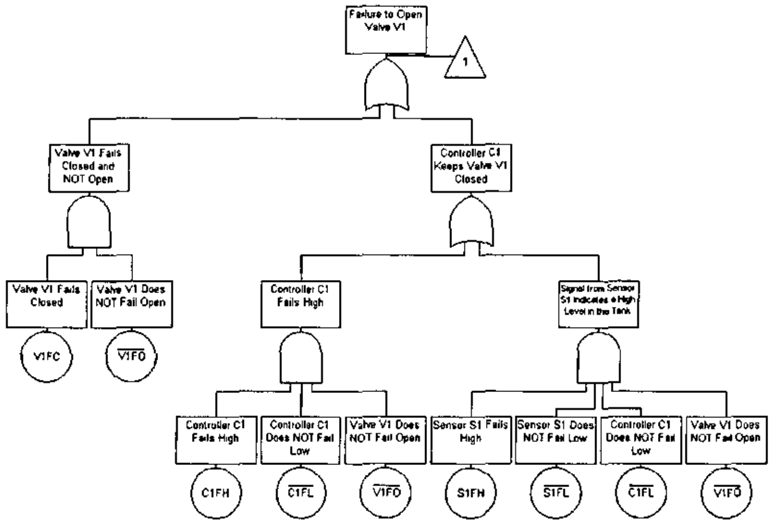


Figure A.23: Non-Coherent fault tree for no flow through valve V1 - transfer 1

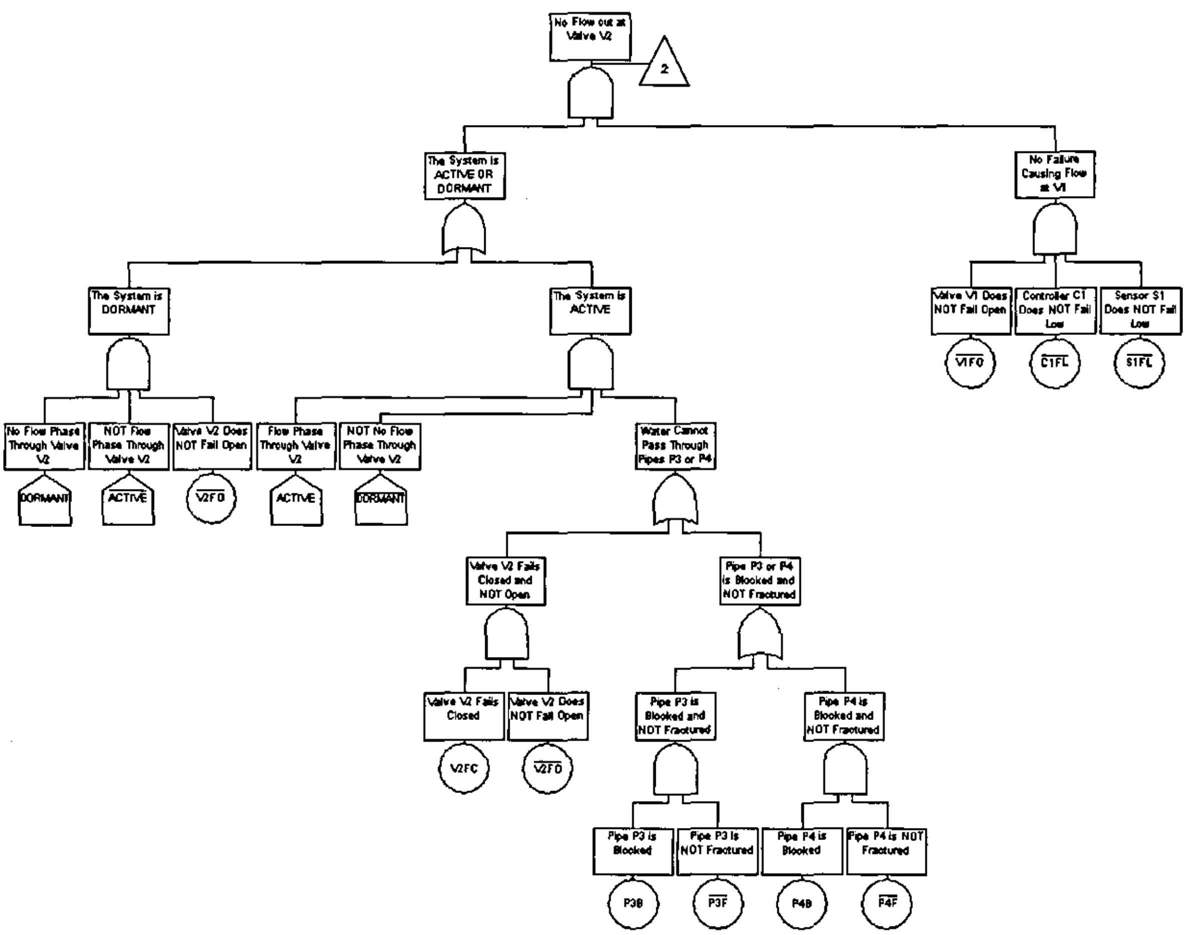


Figure A.24: Non-Coherent fault tree for no flow through valve V1 - transfer 2

Number	Prime Implicants
1)	NWMS
2)	$\mathrm{V1FC}.\overline{\mathrm{V1FO}}$
3)	$\mathrm{P1B}.\overline{\mathrm{P1F}}$
4)	$\mathrm{P1F}.\overline{\mathrm{P1B}}$
5)	$\mathrm{P2B}.\overline{\mathrm{P2F}}$
6)	$\mathrm{C1FH}.\overline{\mathrm{V1FO}}.\overline{\mathrm{C1FL}}$
7)	$\mathrm{S1FH}.\overline{\mathrm{V1FO}}.\overline{\mathrm{C1FL}}.\overline{\mathrm{S1FL}}$
8)	$\mathrm{V2FC}.\overline{\mathrm{V2FO}}$
9)	$\mathrm{P3B}.\overline{\mathrm{P3F}}$
10)	$\mathrm{P4B}.\overline{\mathrm{P4F}}$

Table A.11: Prime implicants for no flow through valve V1

A.2.5 Water in the Overspill Tray

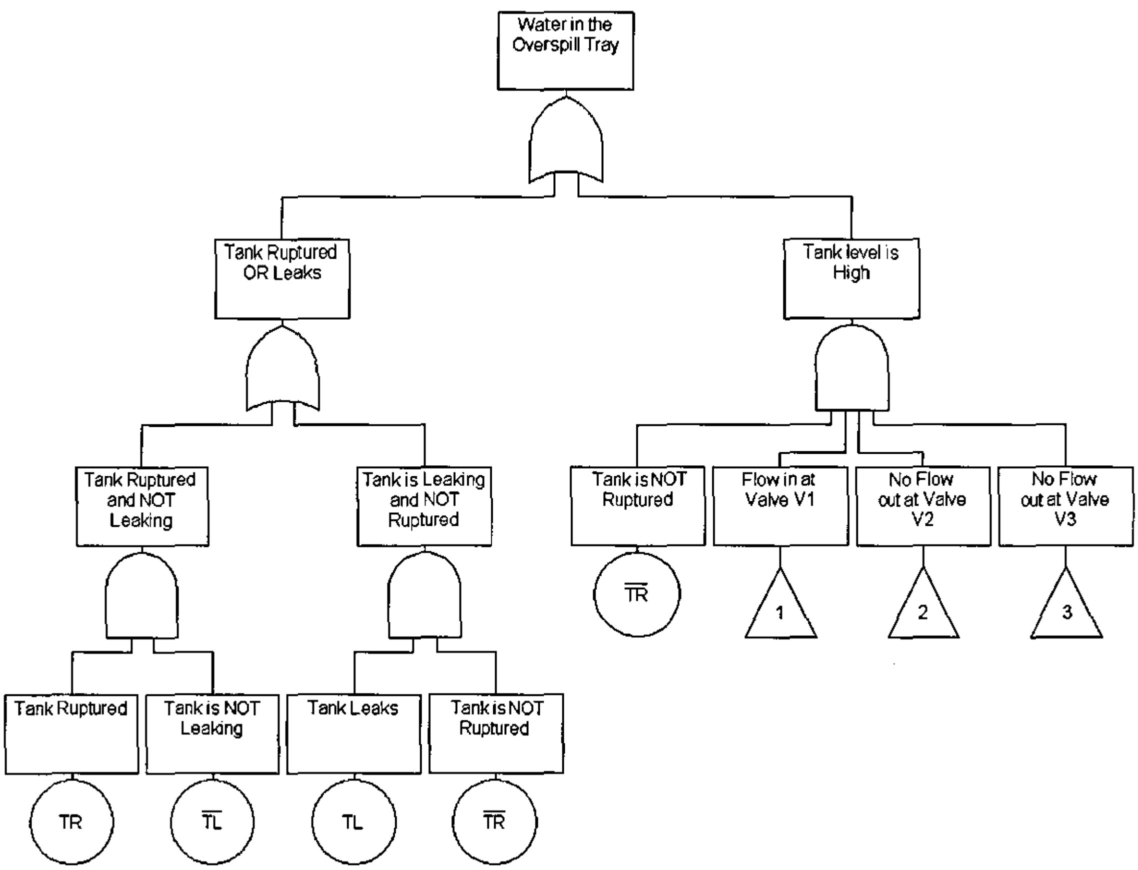


Figure A.25: Non-Coherent fault tree for water in the overspill tray

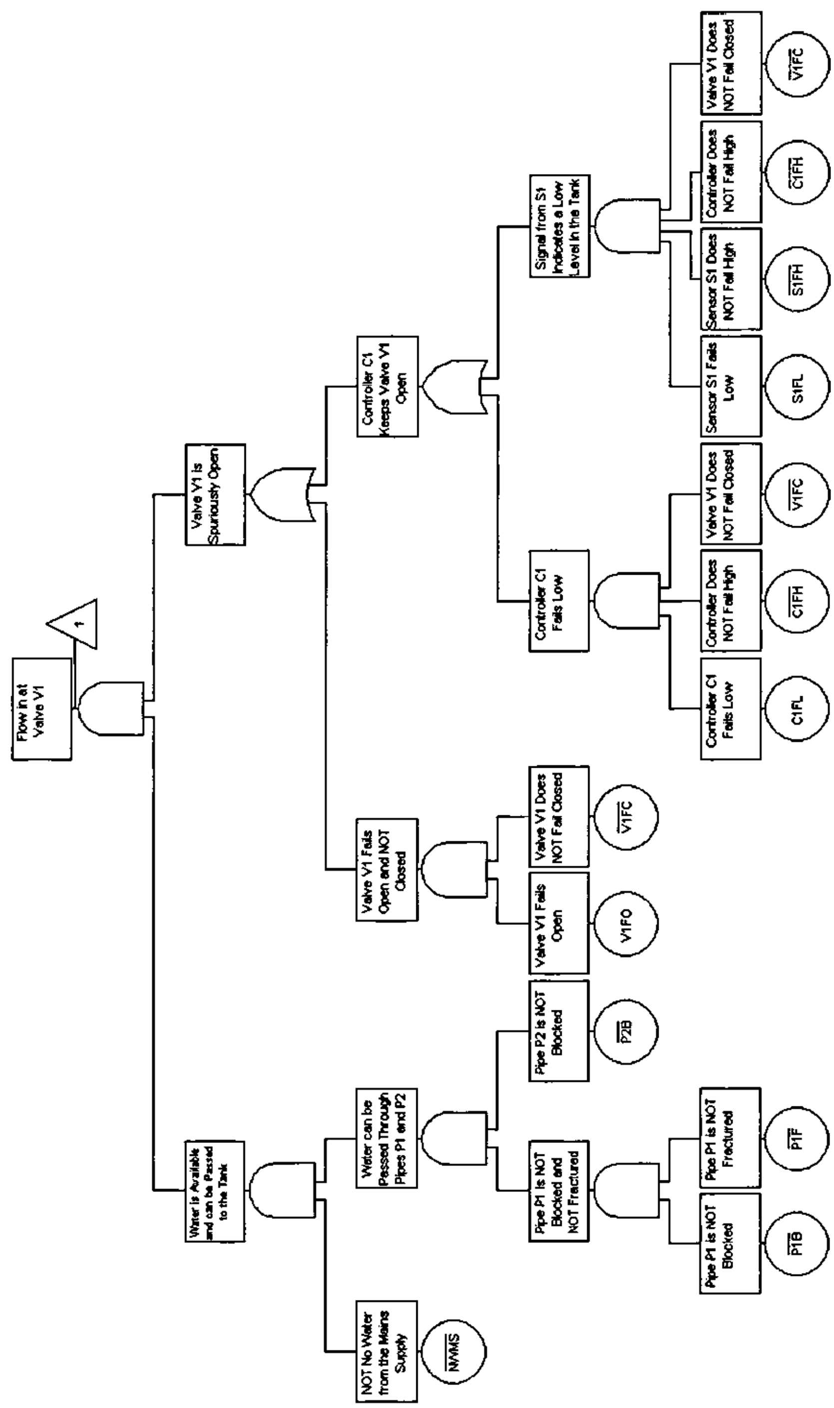


Figure A.26: Non-Coherent fault tree for water in the overspill tray - transfer 1

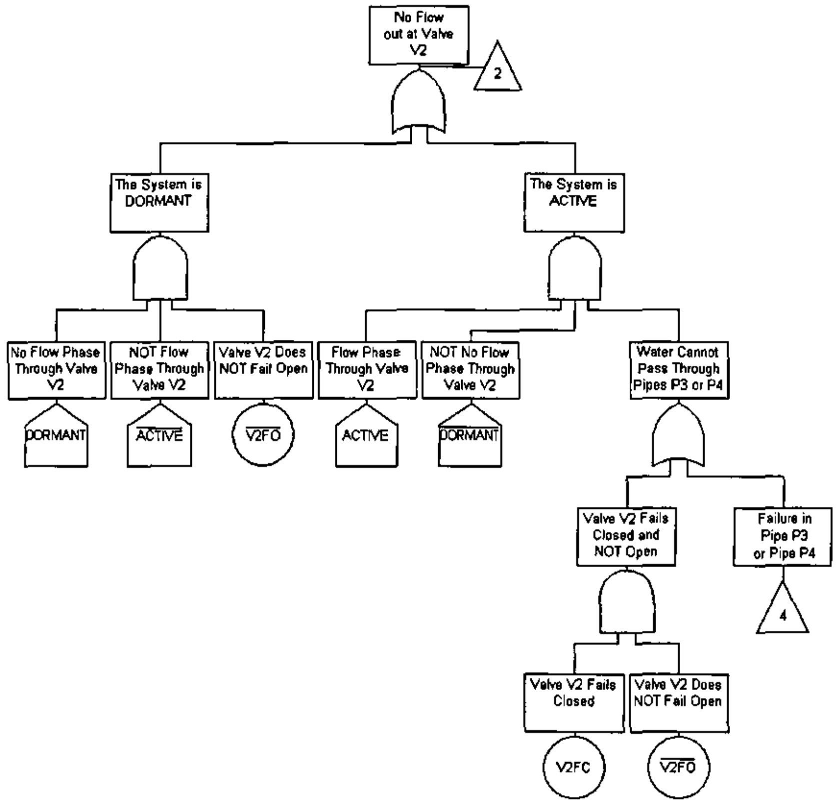


Figure A.27: Non-Coherent fault tree for water in the overspill tray - transfer 2

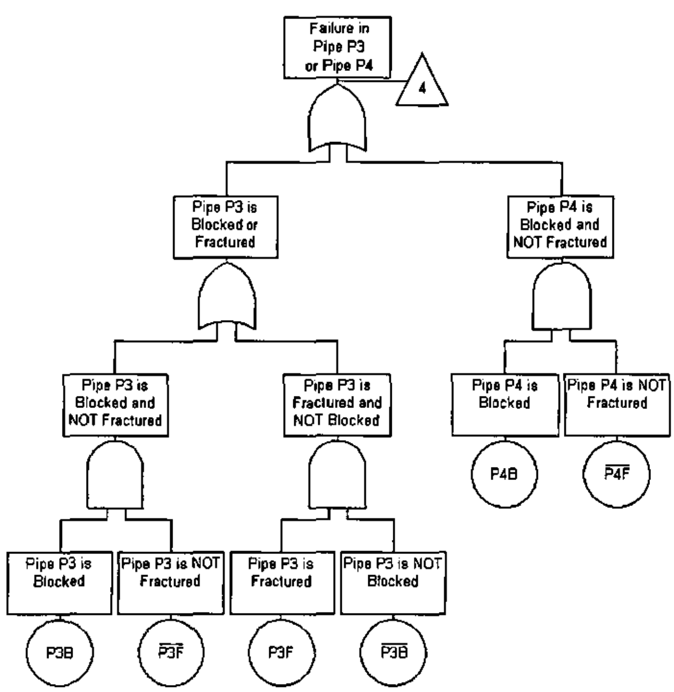


Figure A.28: Non-Coherent fault tree for water in the overspill tray - transfer 4

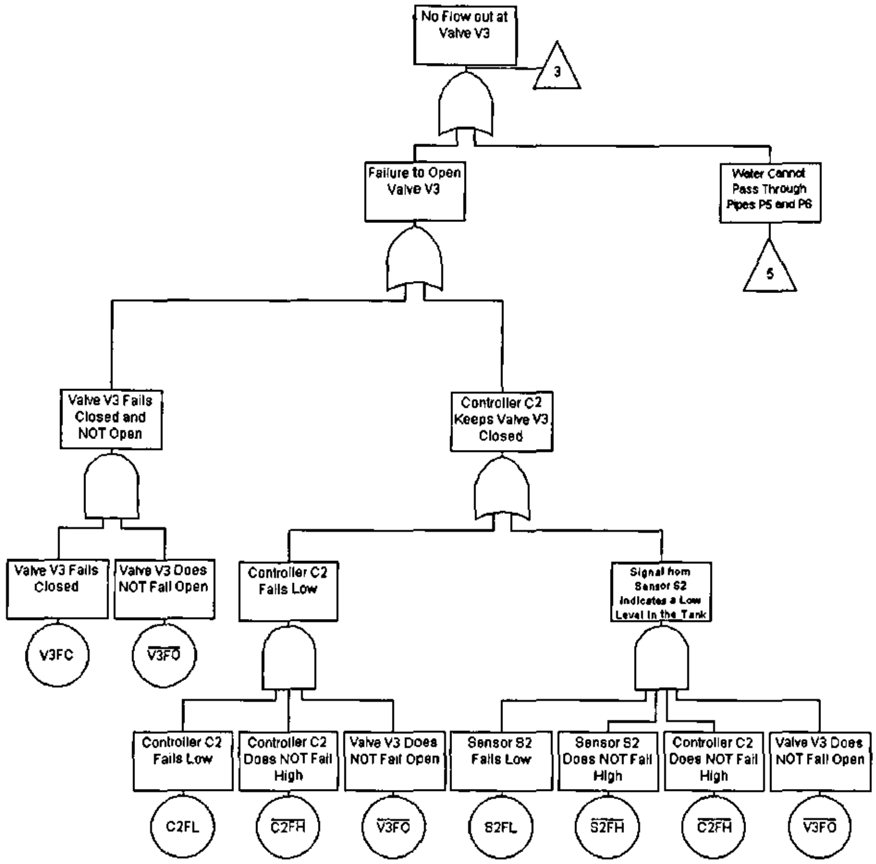


Figure A.29: Non-Coherent fault tree for water in the overspill tray - transfer 3

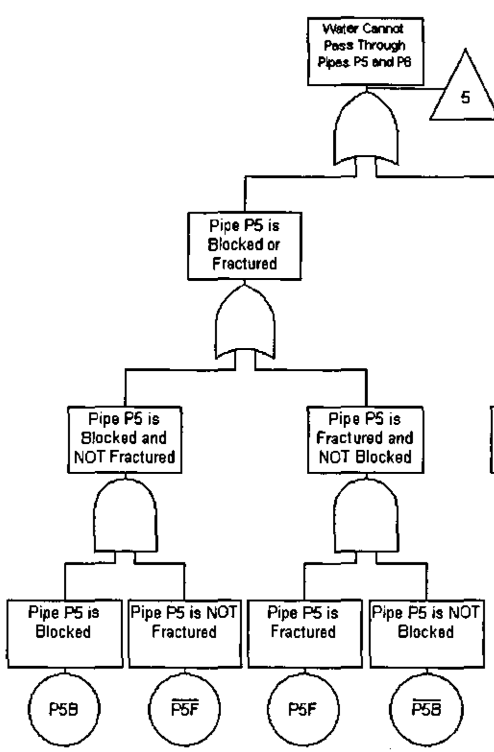


Figure A.30: Non-Coherent fault tree for water in the overspill tray - transfer 5

Number	Prime Implicants
1)	$TR.\overline{TL}$
2)	$TL.\overline{TR}$
3)	$V1FO.V2FC.P5B.\overline{TR}.\overline{V1FC}.\overline{V2FO}.\overline{P5F}$
4)	$V1FO.V2FC.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{P5B}$
5)	$V1FO.V2FC.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{P6F}$
6)	$V1FO.V2FC.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{V3FO}$
7)	$V1FO.V2FC.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{V3FO}.\overline{C2FH}$
8)	$V1FO.V2FC.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
9)	$V1FO.P3B.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{P5F}$
10)	$V1FO.P3B.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{P5B}$
11)	$V1FO.P3B.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{P6F}$
12)	$V1FO.P3B.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{V3FO}$
13)	$V1FO.P3B.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{V3FO}.\overline{C2FH}$
14)	$V1FO.P3B.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3F}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
15)	$V1FO.P3F.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P5F}$
16)	$V1FO.P3F.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P5B}$
17)	$V1FO.P3F.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P6F}$
18)	$V1FO.P3F.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{V3FO}$
19)	$V1FO.P3F.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{V3FO}.\overline{C2FH}$
20)	$V1FO.P3F.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
21)	$V1FO.P4B.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{P5F}$
22)	$V1FO.P4B.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{P5B}$
23)	$V1FO.P4B.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{P6F}$
24)	$V1FO.P4B.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{V3FO}$
25)	$V1FO.P4B.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{V3FO}.\overline{C2FH}$
26)	$V1FO.P4B.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P4F}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
27)	$C1FL.V2FC.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{V2FO}.\overline{P5F}$
28)	$C1FL.V2FC.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{P5B}$
29)	$C1FL.V2FC.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{V2FO}.\overline{P6F}$
30)	$C1FL.V2FC.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{V2FO}.\overline{V3FO}$
31)	$C1FL.V2FC.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{V2FO}.\overline{V3FO}.\overline{C2FH}$
32)	$C1FL.V2FC.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{V2FO}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
33)	$C1FL.P3B.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{P5F}$
34)	$C1FL.P3B.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{P5B}$
35)	$C1FL.P3B.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{P6F}$
36)	$C1FL.P3B.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{V3FO}$
41)	$C1FL.P3F.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{V3FO}$
37)	$C1FL.P3B.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{V3FO}.\overline{C2FH}$
38)	$C1FL.P3B.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3F}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
39)	$C1FL.P3F.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P5F}$
40)	$C1FL.P3F.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P5B}$
41)	$C1FL.P3F.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{P6F}$
42)	$C1FL.P3F.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{P3B}.\overline{V3FO}$
43)	$C1FL.P3F.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3B}.\overline{V3FO}.\overline{C2FH}$
44)	$C1FL.P3F.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P3B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$
45)	$C1FL.P4B.P5B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{P5F}$
46)	$C1FL.P4B.P5F.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{P5B}$
47)	$C1FL.P4B.P6B.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{P6F}$
48)	$C1FL.P4B.V3FC.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{V3FO}$
49)	$C1FL.P4B.C2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{V3FO}.\overline{C2FH}$
50)	$C1FL.P4B.S2FL.\overline{TR}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{NWMS}.\overline{V1FC}.\overline{C1FH}.\overline{P4F}.\overline{V3FO}.\overline{C2FH}.\overline{S2FH}$

Table A.12: Prime implicants for water in the overspill tray when the system is ACTIVE - Table 1

Number	Prime Implicants
51)	S1FL.V2FC.P5B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{P5F}}$
52)	S1FL.V2FC.P5F.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{P5B}}$
53)	S1FL.V2FC.P6B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{P6F}}$
54)	S1FL.V2FC.V3FC.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}$
55)	S1FL.V2FC.C2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
56)	S1FL.V2FC.S2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$
57)	S1FL.P3B.P5B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}$
58)	S1FL.P3B.P5F.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5B}}$
59)	S1FL.P3B.P6B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P6F}}$
60)	S1FL.P3B.V3FC.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V3FO}}$
61)	S1FL.P3B.C2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
62)	S1FL.P3B.S2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$
63)	S1FL.P3F.P5B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}.\overline{\mathrm{P6F}}$
64)	S1FL.P3F.P5F.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}.\overline{\mathrm{P5B}}$
65)	S1FL.P3B.P6B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P6F}}$
66)	S1FL.P3F.V3FC.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}.\overline{\mathrm{V3FO}}$
67)	S1FL.P3F.C2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
68)	S1FL.P3F.S2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P3B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$
69)	S1FL.P4B.P5B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{P5F}}$
70)	S1FL.P4B.P5F.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{P5B}}$
71)	S1FL.P4B.P6B.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{P6F}}$
72)	S1FL.P4B.V3FC.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}$
73)	S1FL.P4B.C2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
74)	S1FL.P4B.S2FL.$\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$

Table A.13: Prime implicants for water in the overspill tray when the system is ACTIVE - Table 2

Number	Prime Implicants
1)	TR.$\overline{\mathrm{TL}}$
2)	TL.$\overline{\mathrm{TR}}$
3)	V1FO.P5B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}$
4)	V1FO.P5F.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5B}}.\overline{\mathrm{V1FC}}$
5)	V1FO.P6B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{P6F}}$
6)	V1FO.V3FC.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{V3FO}}$
7)	V1FO.C2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
8)	V1FO.S2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$
9)	C1FL.P5B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}$
10)	C1FL.P5F.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5B}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}$
11)	C1FL.P6B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{P6F}}$
12)	C1FL.V3FC.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V3FO}}$
13)	C1FL.C2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
14)	C1FL.S2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$
15)	S1FL.P5B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}$
16)	S1FL.P5F.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5B}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}$
17)	S1FL.P6B.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{P6F}}$
18)	S1FL.V3FC.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V3FO}}$
19)	S1FL.C2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
20)	S1FL.S2FL.$\overline{\mathrm{TL}}.\overline{\mathrm{TR}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P3F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FH}}$

Table A.14: Prime implicants for water in the overspill tray when the system is DORMANT

Appendix B

Simulation Description

B.1 Introduction

The program is started from a command prompt requiring five parameters, each of which specify the name of a file. There are two input files containing changes to the default system configuration of the program and the fault trees to be used in the analysis. The remaining three are output files describing how the system is configured, data from the simulation run and fault information for each of the four schemes.

B.2 Input Files

To control how the simulation operates a system description file can be created. This defines values of the simulation's system variables and any component state changes. If no changes are made to the system setup by the user the default values within the program will be used.

B.2.1 System Description File

The system description file is a text file containing comma-separated values. It allows the simulation to be configured to function in a specific way as required by the user. Each line in the file will perform one of three possible actions; set a system variable, change a component state or generate a random failure.

B.2.1.1 System Variables

The simulation variables allow the duration of the simulation and the frequency of the check and print steps to be altered. Each change to the value of a variable in the system description file is defined with the text 'VARIABLE' followed by the name of the variable to set and its new value:

'VARIABLE' ',' < *variable's name* > ',' < *number* >.

The five simulation variables are listed in Table B.1. The variables 'TIMEINC', 'TIMESTART' and 'TIMEEND' allow the time increment, start time and end time of the simulation to be specified respectively. The time increment, '*dt*', is the duration of a single time step between subsequent calculation intervals. Note the simulation does not work in real-time, the time variables only affect the calculation and do not control the simulation's elapsed time.

Variable Name	Description
TIMEINC	Time increment
TIMEEND	End time
TIMESTART	Start time
CHECKSTEP	Time steps between fault checks
PRINTSTEP	Time steps between system prints

Table B.1: Simulation Variables

The PRINTSTEP variable controls how often the states of the components and the values from the sensors are printed to the data file. A PRINTSTEP of '1' would force the components states and sensor measurements to be output to the data file at every time step. The CHECKSTEP variable controls how often a comparison is made between the sensor readings for actual and expected system behaviour. It specifies the number of time increments between checks for failures.

B.2.1.2 Induced Component State Change

A component state change is used to set the state of a component at a specific point in time. Each state change is defined in the system description file with a line of the form:

< *component name* > ',' 'STATE' ',' < *new component state* > [*time*].

The component to change is identified along with the action and the new state. The time of the change can be optionally defined, but will default to $t = 0.00$ if not specified. A list of valid component names and states are shown in Table B.2.

Component Code	Component State	Component Code	Component State
VALVE*i*	OPEN	SENSOR*i*	LOW
$(1 \leq i \leq 3)$	CLOSED	$(1 \leq i \leq 2)$	FAILEDLOW
	FAILEDOPEN		HIGH
	FAILEDCLOSED		FAILEDHIGH
CONTROLLER*i*	LOW	PIPE*i*	NORMAL
$(1 \leq i \leq 2)$	FAILEDLOW	$(1 \leq i \leq 6)$	BLOCKED
	HIGH		FRACTURED
	FAILEDHIGH	MAINSUPPLY	WATER
TANK	NORMAL	MAINSUPPLY	NOWATER
TANK	LEAKING	PHASE	ACTIVE
TANK	RUPTURED	PHASE	DORMANT

Table B.2: State induced changes

B.2.1.3 Random Component Failure

The 'random component failure' feature is used to produce a fixed number of randomly generated component failures at a specified time. Such failures are specified in the system description file with a line of the form:

'RANDOM' ',' < *number* > ',' [*time*].

The line contains the keyword 'RANDOM', followed by the number of failures to create and an optional time at which they should occur (this defaults to 0.00 if not specified).

All components have the same likelihood of failure. Each component selected to be failed is chosen by generating a random number. For all components except the main supply (which only has one possible cause of failure) a second random number is generated to determine the component's failed state.

The random numbers used in the water tank program are generated by the 'rand' function. This is a pseudo random number generator. The sequence of numbers returned is determined by a seed. To try to ensure that each run is different the seed is initialised using the time in seconds from the 'time' function. This gives the number of seconds that have elapsed in a universal time coordinate (since January 1st 1970). Running the program with the same seed and same set of 'RANDOM' commands in the description file would produce the same result as previous runs.

B.2.1.4 UnavailabilityFailure

The 'unavailability failure' feature enables a failure to occur based on the unavailability of the components in the system. Each component has both a failure and repair rate that is used to calculate its unavailability, q_c. Over time as a component is used the likelihood of being unavailable will gradually increase, therefore this is re-calculated at each time step. The format of the input line for the unavailability failure is:

'RANDPROB' ',' < *number* >,

where the keyword is 'RANDPROB' and <*number*> is the number of time steps between the generation of failures.

Failures in the system are simulated by generating a random number for each component between 0 and 1. If the number produced for a component indicates unavailability then it has failed.

B.2.2 Fault Tree Branch File

The fault tree branch file contains the definitions of the branches of the fault trees. Storing the branches in a file allows them to be changed without re-building the water tank system, provided there are no extra component or state names that have not been defined in the program. Each line of the file is formatted to define a named branch of a fault tree:

< *FAULT TREE NAME* > = < *FAULT TREE EXPRESSION* >,

where a fault tree expression is a formatted string that defines a fault tree using the three logical operators: 'AND', 'OR' and 'NOT', together with the terminal component name and state strings, for instance 'V1FO'. A fault tree expression can be written in the following ways:

< *FAULT TREE EXPRESSION* > = (< *WATER TANK COMPONENT STATE* >),
| AND(< *number* >, < *FAULT TREE EXPRESSION** >),
| OR(< *number* >, < *FAULT TREE EXPRESSION** >),
| NOT(< *FAULT TREE EXPRESSION** >),

where '∗' indicates that there can be more than one fault tree expression. An example of a simple fault tree described in this way is: FTV2 = OR(2, NFPV2, V2FO), which is shown in Appendix A, Figure A.3.

B.3 Output Files

The output files are used to redirect the standard output into files that can be analysed after the simulation run has completed.

B.3.1 Configuration File

The configuration file is divided into three sections. The first section contains details of the initial state or value of all the components and variables in the water tank system before any re-configuration takes place, as shown in the example in Figure B.1.

```
Water Tank Simulation - System Configuration
--------------------------------------------

System Phase      : State = Dormant
Controller(1)     : State = High
Controller(2)     : State = High
Main Supply       : State = Water
Over Spill Tray   : State = Empty
Pipe(1)           : State = Normal
Pipe(2)           : State = Normal
Pipe(3)           : State = Normal
Pipe(4)           : State = Normal
Pipe(5)           : State = Normal
Pipe(6)           : State = Normal
Sensor(1)         : State = High
Sensor(2)         : State = High
Tank              : State = Normal
Valve(1)          : State = Closed
Valve(2)          : State = Closed
Valve(3)          : State = Closed
System Variables  : TimeInc = 0.250000,
                    TimeStart = 0.000000,
                    TimeEnd = 1000.000000,
                    CheckStep = 1800,
                    PrintStep = 40,
                    RandPStep = 0
```

```
Failure Rate and Repair Rate Values
 ----------------------------------

 +--------------------------------------------------------------+
 |Component     | State        | Failure Rate | Repair Rate     |
 |--------------------------------------------------------------|
 |Controller1   | FailedLow    | 0.0000074000 | 0.0000000000    |
 |Controller1   | FailedHigh   | 0.0000074000 | 0.0000000000    |
 |...           | ...          | ...          | ...             |

 State Changes Induced at end of stated time point
 -------------------------------------------------

 State Change : Phase, time = 0.000000, state = Active, *** COMMAND INDUCED ***
 State Change : Pipe3, time = 400.000000, state = Blocked, *** COMMAND INDUCED ***
```

Figure B.1: Example system configuration file

The second part consists of a table of initial failure and repair rates for each of the component's failure states. The final section of the file contains a record of each component state change that occurs during the simulation. It records the time the change occurred at and whether the change was induced explicitly by the user or randomly created using one of the three operations, as listed in Table B.3.

State Change Tag	Reason for State Change
*** COMMAND INDUCED ***	Caused by the user issuing a state command in the system description file
*** COMMAND RANDOM ***	Caused by the user issuing the 'RANDOM' Command
*** UNAVAILABILITY FAILURE ***	Random failure dependent upon the component failure rates. System variable 'RANDPROB' is set to greater than zero in the system description file.

Table B.3: State change tags

Note that the simulation applies state changes for a given time at the end of the time interval after the calculation, checking and reporting steps have taken place. Therefore any changes will be apparent at the time increment following the time at which they were applied.

B.3.2 Data File

The data file records the values of flow rates and component states at specified time steps. Each line contains output for a particular time step. The number of time intervals between output lines is controlled using the 'PRINTSTEP' variable. At each iteration of a PRINTSTEP time interval a snapshot of the states of the components in the system together with specific measured values are output to the data file. It is formatted as a comma separated value file that can be tabulated using a spreadsheet. The first row of the file contains the names of components and variables. The file has 28 columns in total, a description of their contents is given in Table B.4.

Column Heading		Description
Time	-	Simulation time point
Water Level	-	The height of water in the tank
Volume	-	The volume of water in the tank
VFi ($1 \leq i \leq 3$)	-	The volume flow rate at sensor VFi
SP1	-	Detects the amount of water coming out of the tank and landing in the tray
TVF2	-	Volume flow rate in pipe P4
TVF3	-	Volume flow rate in pipe P5
DHDT	-	Rate of change of height
DHDTIND	-	Rate of change of height indication
WIND	-	Water level indication
PHASE	-	The current phase the system is in - 'ACTIVE' or 'DORMANT'
Ci ($1 \leq i \leq 2$)	-	The status of controller Ci - 'high', 'low', 'failed high' or 'failed low'
MS	-	The status of water coming from the main supply - 'water' or 'no water'
Pi ($1 \leq i \leq 6$)	-	The status of pipe Pi - 'normal', 'blocked' or 'fractured'
Si ($1 \leq i \leq 2$)	-	The status of sensor Si - 'high', 'low', 'failed high' or 'failed low'
TK	-	The status of the tank - 'normal', 'ruptured' or 'leaking'.
Vi ($1 \leq i \leq 3$)	-	The status of valve Vi - 'open', 'closed', 'failed open' or 'failed closed'

Table B.4: Column headings and description

B.3.3 Fault File

The fault file is a text file containing the results from the fault diagnostic method for each of the four schemes. The simulation is checked for deviations at intervals defined by the system variable 'CHECKSTEP'. At each check interval the fault tree, sensor readings, minimal cut sets (scheme 1) or prime implicants (schemes 2, 3 and 4), importance measures and the most likely cause of failure are recorded in the file for each of the four fault tree schemes. An example fault file for scheme 1 is shown in Figure B.2.

```
Fault Tree Comparsion at Time = 100.000000
--------------------------------------------

Fault Tree for Scheme 1:
---------------------------
                              **********************
OR                            * Minimised cut sets *
 |                            **********************
 1-OR
 |  |                         Contents of cut set MC1 :
 |  1-Sensor2(FailedHigh)     Sensor2(FailedHigh)
 |  |
 |  2-Controller2(FailedHigh) Contents of cut set MC2 :
 |                            Valve3(FailedOpen)
 2-Valve3(FailedOpen)
                              Contents of cut set MC3 :
Sensor Readings:              Controller2(FailedHigh)
----------------
                              ***********************
VF1 = 0.001651                * Importance Measures *
VF2 = 0.000000                ***********************
VF3 = 0.001197
SP1 = Empty                   *** Most likely cause(s) of failure occur at cut set(s) :
                              MC3
```

Figure B.2: Example 'fault file' output for scheme 1

Appendix C

Fault Tree and Success Tree Construction

C.1 Fault Tree Construction

C.1.1 High Flow in Section 1 (V1)

$$
\begin{aligned}
\mathrm{HFV1} &= \overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.(\mathrm{V1FO}.\overline{\mathrm{V1FC}} + \mathrm{C1FL}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}} \\
&\quad + \mathrm{S1FE}.\overline{\mathrm{S1FL}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}} \\
&\quad + \mathrm{S1FL}.\overline{\mathrm{S1FE}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}})
\end{aligned}
$$

Number	Prime Implicants
1)	$\mathrm{V1FO}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V1FC}}$
2)	$\mathrm{C1FL}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}$
3)	$\mathrm{S1FE}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FL}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}$
4)	$\mathrm{S1FL}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FE}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}$

Table C.1: Prime implicants for high flow in section 1 (V1)

Number	Potential Causes of Failure
1)	V1FO
2)	C1FL
3)	S1FE
4)	S1FL

Table C.2: Potential causes of failure for high flow in section 1 (V1) after performing the coherent approximation

C.1.2 High Flow in Section 2 (V2)

$$\mathrm{HFV2} = \overline{\mathrm{V2FC}}.\overline{\mathrm{P3B}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P4B}}.(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}} + \mathrm{V2FO.DORMANT}.\overline{\mathrm{ACTIVE}})$$

The prime implicant obtained for 'high flow in section 2 (V2)' when the system is ACTIVE is:

$$\overline{\mathrm{V2FC}}.\overline{\mathrm{P3B}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P4B}},$$

which is of order 4 and contains only components and states that are known to NOT have failed.

The prime implicant obtained for 'unexpected flow at valve V2' when the system is DORMANT is:

$$\mathrm{V2FO}.\overline{\mathrm{V2FC}}.\overline{\mathrm{P3B}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P4B}},$$

which is of order 5. After performing the coherent approximation the result obtained is 'V2FO'.

C.1.3 High Flow in Section 3 (V3)

$$\begin{aligned}
\mathrm{HFV3} &= \overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P5B}}.(\mathrm{V3FO}.\overline{\mathrm{V3FC}} + \mathrm{C2FH}.\overline{\mathrm{C2FL}}.\overline{\mathrm{V3FC}} \\
&\quad +\mathrm{S2FH}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{V3FC}} \\
&= +\mathrm{S2FVH}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FF}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{V3FC}} \\
&= +\mathrm{S2FF}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{V3FC}})
\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{V3FO}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{V3FC}}$
2)	$\mathrm{C2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}$
3)	$\mathrm{S2FVH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FF}}$
4)	$\mathrm{S2FH}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}$
5)	$\mathrm{S2FF}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{P6B}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FVH}}$

Table C.3: Prime implicants for high flow in section 3 (V3)

Number	Potential Causes of Failure
1)	V3FO
2)	C2FH
3)	S2FH
4)	S2FVH
5)	S2FF

Table C.4: Potential causes of failure for high flow in section 3 (V3) after performing the coherent approximation

C.1.4 Low Flow in Section 1 (V1)

$$\begin{aligned} LFV1 &= NWMS + V1FC.\overline{V1FC} + P1B.\overline{P1F} + P1F.\overline{P1B} + P2B.\overline{P2F} \\ &+ C1FH.\overline{V1FO}.\overline{C1FL} + S1FH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FVH}.\overline{S1FF} \\ &+ S1VFH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FF} \\ &+ S1FF.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FVH} \end{aligned}$$

Number	Prime Implicants
1)	NWMS
2)	$V1FC.\overline{V1FO}$
3)	$P1B.\overline{P1F}$
4)	$P1F.\overline{P1B}$
5)	$P2B.\overline{P2F}$
6)	$C1FH.\overline{V1FO}.\overline{C1FL}$
7)	$S1FH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FVH}.\overline{S1FF}$
8)	$S1FVH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FF}$
9)	$S1FF.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FVH}$

Table C.5: Prime implicants for low flow in section 1 (V1)

Number	Potential Causes of Failure
1)	NWMS
2)	V1FC
3)	P1B
4)	P1F
5)	P2B
6)	C1FH
7)	S1FH
8)	S1FVH
9)	S1FF

Table C.6: Potential causes of failure for low flow in section 1 (V1) after performing the coherent approximation

C.1.5 Low Flow in Section 3 (V3)

$$\begin{aligned} LFV3 &= P5B.\overline{P5F} + P5F.\overline{P5B} + P6B.\overline{P6F} + V3FC.\overline{V3FO} \\ &+ C2FL.\overline{V3FO}.\overline{C2FH} + S2FE.\overline{V3FO}.\overline{C2FH}.\overline{S2FL}.\overline{S2FH}.\overline{S2FVH}.\overline{S2FF} \\ &+ S2FL.\overline{V3FO}.\overline{C2FH}.\overline{S2FE}.\overline{S2FH}.\overline{S2FVH}.\overline{S2FF} \end{aligned}$$

Number	Prime Implicants
1)	$\text{P5B}.\overline{\text{P5F}}$
2)	$\text{P5F}.\overline{\text{P5B}}$
3)	$\text{P6B}.\overline{\text{P6F}}$
4)	$\text{V3FC}.\overline{\text{V3FO}}$
5)	$\text{C2FL}.\overline{\text{V3FO}}.\overline{\text{C2FH}}$
6)	$\text{S2FE}.\overline{\text{V3FO}}.\overline{\text{C2FH}}.\overline{\text{S2FL}}.\overline{\text{S2FH}}.\overline{\text{S2FVH}}.\overline{\text{S2FF}}$
7)	$\text{S2FL}.\overline{\text{V3FO}}.\overline{\text{C2FH}}.\overline{\text{S2FE}}.\overline{\text{S2FH}}.\overline{\text{S2FVH}}.\overline{\text{S2FF}}$

Table C.7: Prime implicants for low flow in section 3 (V3)

Number	Potential Causes of Failure
1)	P5B
2)	P5F
3)	P6B
4)	V3FC
5)	C2FL
6)	S2FE
7)	S2FL

Table C.8: Potential causes of failure for low flow in section 3 (V3) after performing the coherent approximation

C.1.6 Tray Level in Section 4

$$\text{TRAYL} = \text{TR}.\overline{\text{TL}} + \text{TL}.\overline{\text{TR}}$$

Number	Prime Implicants
1)	$\text{TR}.\overline{\text{TL}}$
2)	$\text{TL}.\overline{\text{TR}}$

Table C.9: Prime implicants for tray level in section 4

Number	Potential Causes of Failure
1)	TR
2)	TL

Table C.10: Potential causes of failure for tray level in section 4 after performing the coherent approximation

C.1.7 Tank Level Pattern Decreasing

$$
\begin{aligned}
\mathrm{TANKDECL} = {} & \mathrm{ACTIVE.\overline{DORMANT}(TL.\overline{TR} + TR.\overline{TL}} \\
& \mathrm{+P5F.\overline{P5B} + \overline{P5B}.\overline{P5F}.\overline{P6B}.(V3FO.\overline{V3FC} + C2FH.\overline{V3FC}.\overline{C2FL}} \\
& \mathrm{+S2FH.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FVH}.\overline{S2FF}} \\
& \mathrm{+S2FVH.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FH}.\overline{S2FF}} \\
& \mathrm{+S2FF.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FVH}.\overline{S2FVH})} \\
& \mathrm{NWMS + V1FC.\overline{V1FC} + P1B.\overline{P1F} + P1F.\overline{P1B} + P2B.\overline{P2F}} \\
& \mathrm{+C1FH.\overline{V1FO}.\overline{C1FL} + S1FH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FVH}.\overline{S1FF}} \\
& \mathrm{+S1FVH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FF}} \\
& \mathrm{+S1FF.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FVH})} \\
& \mathrm{+DORMANT.\overline{ACTIVE}.(TR.\overline{TL} + P5F.\overline{P5B}} \\
& \mathrm{+\overline{P5B}.\overline{P5F}.\overline{P6B}.(V3FO.\overline{V3FC} + C2FH.\overline{V3FC}.\overline{C2FL}} \\
& \mathrm{+S2FH.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FVH}.\overline{S2FF}} \\
& \mathrm{+S2FVH.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FH}.\overline{S2FF}} \\
& \mathrm{+S2FF.\overline{V3FC}.\overline{C2FL}.\overline{S2FE}.\overline{S2FL}.\overline{S2FVH}.\overline{S2FVH})} \\
& \mathrm{+TL.\overline{TR}.(V2FO.\overline{V2FC} + P3F.\overline{P3B})} \\
& \mathrm{+(TL.\overline{TR} + V2FO.\overline{V2FC} + P3F.\overline{P3B}).(NWMS + V1FC.\overline{V1FC}} \\
& \mathrm{+P1B.\overline{P1F} + P1F.\overline{P1B} + P2B.\overline{P2F} + C1FH.\overline{V1FO}.\overline{C1FL}} \\
& \mathrm{+S1FH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FVH}.\overline{S1FF}} \\
& \mathrm{+S1VFH.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FF}} \\
& \mathrm{+S1FF.\overline{V1FO}.\overline{C1FL}.\overline{S1FE}.\overline{S1FL}.\overline{S1FH}.\overline{S1FVH}))}
\end{aligned}
$$

Number	Prime Implicants	Number	Potential Causes of Failure
1)	NWMS	10)	$\mathrm{S1FH.\overline{S1FE}.\overline{S1FL}.\overline{C1FL}.\overline{V1FO}}$
2)	$\mathrm{TL.\overline{TR}}$	11)	$\mathrm{S1FVH.\overline{S1FE}.\overline{S1FL}.\overline{C1FL}.\overline{V1FO}}$
3)	$\mathrm{TR.\overline{TL}}$	12)	$\mathrm{S1FF.\overline{S1FE}.\overline{S1FL}.\overline{C1FL}.\overline{V1FO}}$
4)	$\mathrm{P5F.\overline{P5B}}$	13)	$\mathrm{V3FO.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{V3FC}}$
5)	$\mathrm{V1FC.\overline{V1FO}}$	14)	$\mathrm{C2FH.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{C2FL}.\overline{V3FC}}$
6)	$\mathrm{P1B.\overline{P1F}}$	15)	$\mathrm{S2FH.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{S2FE}.\overline{S2FL}.\overline{S2FVH}.\overline{S2FF}.\overline{C2FL}.\overline{V3FC}}$
7)	$\mathrm{P1F.\overline{P1B}}$	16)	$\mathrm{S2FVH.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{S2FE}.\overline{S2FL}.\overline{S2FH}.\overline{S2FF}.\overline{C2FL}.\overline{V3FC}}$
8)	$\mathrm{P2B.\overline{P2F}}$	17)	$\mathrm{S2FF.\overline{P5B}.\overline{P5F}.\overline{P6B}.\overline{S2FE}.\overline{S2FL}.\overline{S2FH}.\overline{S2FVH}.\overline{C2FL}.\overline{V3FC}}$
9)	$\mathrm{C1FH.\overline{C1FL}.\overline{V1FO}}$		

Table C.11: Prime implicants for tank level pattern decreasing in the ACTIVE operating mode

Number	Potential Causes of Failure
1)	NWMS
2)	TL
3)	TR
4)	P5F
5)	V1FC
6)	P1B
7)	P1F
8)	P2B
9)	C1FH
10)	S1FH
11)	S1FVH
12)	S1FF
13)	V3FO
14)	C2FH
15)	S2FH
16)	S2FVH
17)	S2FF

Table C.12: Potential causes of failure for tank level pattern decreasing in the ACTIVE operating mode after performing the coherent approximation

Number	Prime Implicants
1)	TR.$\overline{TL}$
2)	P5F.$\overline{P5B}$
3)	NWMS.TL.$\overline{TR}$
4)	NWMS.V2FO.$\overline{V2FC}$
5)	NWMS.P3F.$\overline{P3B}$
6)	TL.V2FO.$\overline{TR}$.$\overline{V2FC}$
7)	TL.P3F.$\overline{TR}$.$\overline{P3B}$
8)	V1FC.V2FO.$\overline{V1FO}$.$\overline{V2FC}$
9)	P1B.V2FO.$\overline{P1F}$.$\overline{V2FC}$
10)	P1F.V2FO.$\overline{P1B}$.$\overline{V2FC}$
11)	P2B.V2FO.$\overline{P2F}$.$\overline{V2FC}$
12)	V1FC.P3F.$\overline{V1FO}$.$\overline{P3B}$
13)	P1B.P3F.$\overline{P1F}$.$\overline{P3B}$
14)	P1F.P3F.$\overline{P1B}$.$\overline{P3B}$
15)	P2B.P3F.$\overline{P2F}$.$\overline{P3B}$
16)	V1FC.TL.$\overline{V1FO}$.$\overline{TR}$
17)	P1B.TL.$\overline{P1F}$.$\overline{TR}$
18)	P1F.TL.$\overline{P1B}$.$\overline{TR}$

Number	Potential Causes of Failure
19)	P2B.TL.$\overline{P2F}$.$\overline{TR}$
20)	V3FO.$\overline{P5B}$.$\overline{P5F}$.$\overline{P6B}$.$\overline{V3FC}$
21)	C1FH.V2FO.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{V2FC}$
22)	C1FH.P3F.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{P3B}$
23)	C1FH.TL.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{TR}$
24)	C2FH.$\overline{P5B}$.$\overline{P5F}$.$\overline{P6B}$.$\overline{C2FL}$.$\overline{V3FC}$
25)	S1FH.V2FO.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{V2FC}$
26)	S1FVH.V2FO.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{V2FC}$
27)	S1FF.V2FO.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{V2FC}$
28)	S1FH.P3F.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{P3B}$
29)	S1FVH.P3F.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{P3B}$
30)	S1FF.P3F.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{P3B}$
31)	S1FH.TL.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{TR}$
32)	S1FVH.TL.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{TR}$
33)	S1FF.TL.$\overline{S1FE}$.$\overline{S1FL}$.$\overline{C1FL}$.$\overline{V1FO}$.$\overline{TR}$
34)	S2FH.$\overline{P5B}$.$\overline{P5F}$.$\overline{P6B}$.$\overline{S2FE}$.$\overline{S2FL}$.$\overline{S2FVH}$.$\overline{S2FF}$.$\overline{C2FL}$.$\overline{V3FC}$
35)	S2FVH.$\overline{P5B}$.$\overline{P5F}$.$\overline{P6B}$.$\overline{S2FE}$.$\overline{S2FL}$.$\overline{S2FH}$.$\overline{S2FF}$.$\overline{C2FL}$.$\overline{V3FC}$
36)	S2FF.$\overline{P5B}$.$\overline{P5F}$.$\overline{P6B}$.$\overline{S2FE}$.$\overline{S2FL}$.$\overline{S2FH}$.$\overline{C2FL}$.$\overline{V3FC}$

Table C.13: Prime implicants for tank level pattern decreasing in the DORMANT operating mode

Number	Potential Causes of Failure
1)	TR
2)	P5F
3)	V3FO
4)	C2FH
5)	S2H
6)	S2FVH
7)	S2FF
8)	V1FC.V2FO
9)	C1FH.V2FO
10)	S1FH.V2FO
11)	S1FVH.V2FO
12)	S1FF.V2FO
13)	P1B.V2FO
14)	P1F.V2FO
15)	P2B.V2FO
16)	NWMS.V2FO
17)	V1FC.P3F
18)	C1FH.P3F
19)	S1FH.P3F
20)	S1FVH.P3F
21)	S1FF.P3F
22)	P1B.P3F
23)	P1F.P3F
24)	P2B.P3F
25)	NWMS.P3F
26)	V1FC.TL
27)	C1FH.TL
28)	S1FH.TL
29)	S1FVH.TL
30)	S1FF.TL
31)	P1B.TL
32)	P1F.TL
33)	P2B.TL
34)	NWMS.TL
35)	V2FO.TL
36)	P3F.TL

Table C.14: Potential causes of failure for tank level pattern decreasing in the DORMANT operating mode after performing the coherent approximation

C.1.8 Tank Level Pattern Oscillating

$$
\begin{aligned}
\mathrm{TANKOS} &= \overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}.\overline{\mathrm{V3FO}} \\
&= .\overline{\mathrm{C2FH}}.(\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.(\mathrm{V1FO}.\overline{\mathrm{V1FC}} + \mathrm{C1FL}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}} \\
&\quad + \mathrm{S1FE}.\overline{\mathrm{S1FL}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}} \\
&\quad + \mathrm{S1FL}.\overline{\mathrm{S1FE}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{V1FC}}).(\overline{\mathrm{ACTIVE}}.\overline{\mathrm{V2FO}} \\
&\quad + \mathrm{ACTIVE}.(\mathrm{V2FC}.\overline{\mathrm{V2FO}} + \mathrm{P3B}.\overline{\mathrm{P3F}} + \mathrm{P4B}.\overline{\mathrm{P4F}})))
\end{aligned}
$$

Number	Prime Implicants
1)	$\mathrm{V1FO.V2FC}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
2)	$\mathrm{V1FO.P3B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P3F}}$
3)	$\mathrm{V1FO.P4B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$
4)	$\mathrm{C1FL.V2FC}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
5)	$\mathrm{C1FL.P3B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P3F}}$
6)	$\mathrm{C1FL.P4B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$
7)	$\mathrm{S1FE.V2FC}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
8)	$\mathrm{S1FL.V2FC}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
9)	$\mathrm{S1FE.P3B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P3F}}$
10)	$\mathrm{S1FL.P3B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P3F}}$
11)	$\mathrm{S1FE.P4B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$
12)	$\mathrm{S1FL.P4B}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$

Table C.15: Prime implicants for tank level pattern oscillating in the ACTIVE operating mode

Number	Prime Implicants
1)	$\mathrm{V1FO}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.$
2)	$\mathrm{C1FL}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.$
3)	$\mathrm{S1FE}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.$
4)	$\mathrm{S1FL}.\overline{\mathrm{TR}}.\overline{\mathrm{P5B}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FL}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.$

Table C.16: Prime implicants for tank level pattern oscillating in the DORMANT operating mode

Number	Potential Causes of Failure	Number	Potential Causes of Failure
1)	V1FO.V2FC	7)	S1FE.V2FC
2)	V1FO.P3B	8)	S1FE.P3B
3)	V1FO.P4B	9)	S1FE.P4B
4)	C1FL.V2FC	10)	S1FL.V2FC
5)	C1FL.P3B	11)	S1FL.P3B
6)	C1FL.P4B	12)	S1FL.P4B

Table C.17: Potential causes of failure for tank level pattern oscillating in the ACTIVE operating mode after performing the coherent approximation

Number	Potential Causes of Failure
1)	V1FO
2)	C1FL
3)	S1FE
4)	S1FL

Table C.18: Potential causes of failure for tank level pattern oscillating in the DORMANT operating mode after performing the coherent approximation

C.1.9 Tank Level Pattern Increasing to Full

$$
\begin{aligned}
\mathrm{TANKINCF} &= \overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.(\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.(\mathrm{V1FO}.\overline{\mathrm{V1FC}} + \mathrm{C1FL}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}} \\
&= +\mathrm{S1FE}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FL}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}} \\
&= +\mathrm{S1FL}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FE}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}).(\overline{\mathrm{ACTIVE}}.\overline{\mathrm{V2FO}} \\
&\quad +\mathrm{ACTIVE}.(\mathrm{V2FC}.\overline{\mathrm{V2FO}} + \mathrm{P3B}.\overline{\mathrm{P3F}} + \mathrm{P4B}.\overline{\mathrm{P4F}}).(\mathrm{P5B}.\overline{\mathrm{P5F}} \\
&\quad +\mathrm{P6B}.\overline{\mathrm{P6F}} + \mathrm{V3FC}.\overline{\mathrm{V3FO}} + \mathrm{C2FL}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FH}} \\
&\quad +\mathrm{S2FE}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FL}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}} \\
&\quad +\mathrm{S2FL}.\overline{\mathrm{V3FC}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FE}}.\overline{\mathrm{S2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}))
\end{aligned}
$$

Number	Prime Implicants
1)	$\mathrm{V1FO.P3B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}$
2)	$\mathrm{V1FO.V2FC.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
3)	$\mathrm{V1FO.P3B.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}$
4)	$\mathrm{C1FL.P3B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}$
5)	$\mathrm{V1FO.P3B.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P6F}}$
6)	$\mathrm{V1FO.P4B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$
7)	$\mathrm{V1FO.V2FC.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}$
8)	$\mathrm{C1FL.V2FC.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}$
9)	$\mathrm{V1FO.V2FC.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{P6F}}$
10)	$\mathrm{C1FL.P3B.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}$
11)	$\mathrm{V1FO.P3B.C2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
12)	$\mathrm{C1FL.P3B.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P6F}}$
13)	$\mathrm{V1FO.P4B.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}$
14)	$\mathrm{C1FL.P4B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}$
15)	$\mathrm{V1FO.P4B.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}.\overline{\mathrm{P6F}}$
16)	$\mathrm{C1FL.V2FC.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}$
17)	$\mathrm{V1FO.V2FC.C2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
18)	$\mathrm{C1FL.V2FC.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{P6F}}$
19)	$\mathrm{C1FL.P3B.C2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
20)	$\mathrm{C1FL.P4B.V3FC.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}$
21)	$\mathrm{V1FO.P4B.C2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
22)	$\mathrm{C1FL.P4B.P6B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{P4F}}.\overline{\mathrm{P6F}}$
23)	$\mathrm{C1FL.V2FC.C2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V2FO}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}$
24)	$\mathrm{V1FO.P3B.S2FE.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}$
25)	$\mathrm{V1FO.P3B.S2FL.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}$
26)	$\mathrm{V1FO.P3B.S2FH.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}$
27)	$\mathrm{S1FE.P3B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}$
28)	$\mathrm{S1FL.P3B.P5B.}\overline{\mathrm{TR}}.\overline{\mathrm{P3F}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V1FC}}.\overline{\mathrm{C1FH}}.\overline{\mathrm{S1FH}}.\overline{\mathrm{S1FVH}}.\overline{\mathrm{S1FF}}.\overline{\mathrm{NWMS}}.\overline{\mathrm{P1B}}.\overline{\mathrm{P1F}}.\overline{\mathrm{P2B}}$

Table C.19: Prime implicants for tank level pattern increasing to full in the ACTIVE operating mode

Number	Prime Implicants
29)	C1FL.P4B.C2FL.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH
30)	V1FO.V2FC.S2FE.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
31)	V1FO.V2FC.S2FL.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
32)	V1FO.V2FC.S2FH.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
33)	S1FE.V2FC.P5B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO
34)	S1FL.V2FC.P5B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO
35)	S1FE.P3B.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO
36)	S1FL.P3B.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO
37)	C1FL.P3B.S2FE.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
38)	C1FL.P3B.S2FL.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
39)	C1FL.P3B.S2FH.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
40)	S1FE.P3B.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P6F
41)	S1FL.P3B.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P6F
42)	V1FO.P4B.S2FE.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
43)	V1FO.P4B.S2FL.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
44)	V1FO.P4B.S2FH.TR.P3F.P5F.V1FC.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
45)	S1FE.P4B.P5B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F
46)	S1FL.P4B.P5B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F
47)	S1FE.V2FC.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO
48)	S1FL.V2FC.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO
49)	S1FE.V2FC.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH
50)	S1FL.V2FC.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH
51)	C1FL.V2FC.S2FE.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
52)	C1FL.V2FC.S2FL.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
53)	C1FL.V2FC.S2FH.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
54)	S1FE.V2FC.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.P6F
55)	S1FL.V2FC.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.P6F
56)	S1FE.P3B.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH
57)	S1FL.P3B.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH
58)	S1FE.P4B.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO
59)	S1FL.P4B.V3FC.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO
60)	C1FL.P4B.S2FE.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
61)	C1FL.P4B.S2FL.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
62)	C1FL.P4B.S2FH.TR.P3F.P5F.V1FC.C1FH.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
63)	S1FE.P4B.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.P6F
64)	S1FL.P4B.P6B.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.P6F
65)	S1FE.P3B.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
66)	S1FL.P3B.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
67)	S1FE.P4B.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH
68)	S1FL.P4B.C2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH
69)	S1FE.P3B.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
70)	S1FL.P3B.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
71)	S1FE.P3B.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
72)	S1FL.P3B.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
73)	S1FE.V2FC.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.S2FVH.S2FF
74)	S1FL.V2FC.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.S2FVH.S2FF
75)	S1FE.P4B.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
76)	S1FL.P4B.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
77)	S1FE.P4B.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V3FO.C2FH.S2FVH.S2FF
78)	S1FL.P4B.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
79)	S1FE.P4B.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
80)	S1FL.P4B.S2FH.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.P4F.V3FO.C2FH.S2FVH.S2FF
81)	S1FE.V2FC.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
82)	S1FL.V2FC.S2FE.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
83)	S1FE.V2FC.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF
84)	S1FL.V2FC.S2FL.TR.P3F.P5F.V1FC.C1FH.S1FH.S1FVH.S1FF.NWMS.P1B.P1F.P2B.V2FO.V3FO.C2FH.S2FVH.S2FF

Table C.20: Prime implicants for tank level pattern increasing to full in the ACTIVE operating mode

Number	Potential Causes of Failure	Number	Potential Causes of Failure
1)	V1FO.V2FC.V3FC	43)	S1FE.V2FC.V3FC
2)	V1FO.V2FC.C2FL	44)	S1FE.V2FC.C2FL
3)	V1FO.V2FC.S2FE	45)	S1FE.V2FC.S2FE
4)	V1FO.V2FC.S2FL	46)	S1FE.V2FC.S2FL
5)	V1FO.V2FC.S2FH	47)	S1FE.V2FC.S2FH
6)	V1FO.V2FC.P5B	48)	S1FE.V2FC.P5B
7)	V1FO.V2FC.P6B	49)	S1FE.V2FC.P6B
8)	V1FO.P3B.V3FC	50)	S1FE.P3B.V3FC
9)	V1FO.P3B.C2FL	51)	S1FE.P3B.C2FL
10)	V1FO.P3B.S2FE	52)	S1FE.P3B.S2FE
11)	V1FO.P3B.S2FL	53)	S1FE.P3B.S2FL
12)	V1FO.P3B.S2FH	54)	S1FE.P3B.S2FH
13)	V1FO.P3B.P5B	55)	S1FE.P3B.P5B
14)	V1FO.P3B.P6B	56)	S1FE.P3B.P6B
15)	V1FO.P4B.V3FC	57)	S1FE.P4B.V3FC
16)	V1FO.P4B.C2FL	58)	S1FE.P4B.C2FL
17)	V1FO.P4B.S2FE	59)	S1FE.P4B.S2FE
18)	V1FO.P4B.S2FL	60)	S1FE.P4B.S2FL
19)	V1FO.P4B.S2FH	61)	S1FE.P4B.S2FH
20)	V1FO.P4B.P5B	62)	S1FE.P4B.P5B
21)	V1FO.P4B.P6B	63)	S1FE.P4B.P6B
22)	C1FL.V2FC.V3FC	64)	S1FL.V2FC.V3FC
23)	C1FL.V2FC.C2FL	65)	S1FL.V2FC.C2FL
24)	C1FL.V2FC.S2FE	66)	S1FL.V2FC.S2FE
25)	C1FL.V2FC.S2FL	67)	S1FL.V2FC.S2FL
26)	C1FL.V2FC.S2FH	68)	S1FL.V2FC.S2FH
27)	C1FL.V2FC.P5B	69	S1FL.V2FC.P5B
28)	C1FL.V2FC.P6B	70)	S1FL.V2FC.P6B
29)	C1FL.P3B.V3FC	71)	S1FL.P3B.V3FC
30)	C1FL.P3B.C2FL	72)	S1FL.P3B.C2FL
31)	C1FL.P3B.S2FE	73)	S1FL.P3B.S2FE
32)	C1FL.P3B.S2FL	74)	S1FL.P3B.S2FL
33)	C1FL.P3B.S2FH	75)	S1FL.P3B.S2FH
34)	C1FL.P3B.P5B	76)	S1FL.P3B.P5B
35)	C1FL.P3B.P6B	77)	S1FL.P3B.P6B
36)	C1FL.P4B.V3FC	78)	S1FL.P4B.V3FC
37)	C1FL.P4B.C2FL	79)	S1FL.P4B.C2FL
38)	C1FL.P4B.S2FE	80)	S1FL.P4B.S2FE
39)	C1FL.P4B.S2FL	81)	S1FL.P4B.S2FL
40)	C1FL.P4B.S2FH	82)	S1FL.P4B.S2FH
41)	C1FL.P4B.P5B	83)	S1FL.P4B.P5B
42)	C1FL.P4B.P6B	84)	S1FL.P4B.P6B

Table C.21: Potential causes of failure for tank level pattern increasing to full in the ACTIVE operating mode after performing the coherent approximation

Number	Prime Implicants
1)	$V1FO.V3FC.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}$
2)	$V1FO.P5B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}$
3)	$V1FO.P6B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{P6F}$
4)	$C1FL.P5B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}$
5)	$C1FL.V3FC.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}$
6)	$V1FO.C2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}$
7)	$C1FL.P6B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{P6F}$
8)	$C1FL.C2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}$
9)	$V1FO.S2FE.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
10)	$V1FO.S2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
11)	$V1FO.S2FH.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
12)	$S1FE.P5B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}$
13)	$S1FL.P5B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}$
14)	$S1FE.V3FC.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}$
15)	$S1FL.V3FC.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}$
16)	$C1FL.S2FE.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
17)	$C1FL.S2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
18)	$C1FL.S2FH.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
19)	$S1FE.P6B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{P6F}$
20)	$S1FL.P6B.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{P6F}$
21)	$S1FE.C2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}$
22)	$S1FL.C2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}$
23)	$S1FE.S2FE.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
24)	$S1FL.S2FE.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
25)	$S1FE.S2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
26)	$S1FL.S2FL.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
27)	$S1FE.S2FH.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$
28)	$S1FL.S2FH.\overline{TR}.\overline{P3F}.\overline{P5F}.\overline{V1FC}.\overline{C1FH}.\overline{S1FH}.\overline{S1FVH}.\overline{S1FF}.\overline{NWMS}.\overline{P1B}.\overline{P1F}.\overline{P2B}.\overline{V3FO}.\overline{C2FH}.\overline{S2FVH}.\overline{S2FF}$

Table C.22: Prime implicants for tank level pattern increasing to full in the DORMANT operating mode

Number	Potential Causes of Failure	Number	Potential Causes of Failure
1)	V1FO.V3FC	15)	S1FE.V3FC
2)	V1FO.C2FL	16)	S1FE.C2FL
3)	V1FO.S2FE	17)	S1FE.S2FE
4)	V1FO.S2FL	18)	S1FE.S2FL
5)	V1FO.S2FH	19)	V1FO.S2FH
6)	V1FO.P5B	20)	S1FE.P5B
7)	V1FO.P6B	21)	S1FE.P6B
8)	C1FL.V3FC	22)	S1FL.V3FC
9)	C1FL.C2FL	23)	S1FL.C2FL
10)	C1FL.S2FE	24)	S1FL.S2FE
11)	C1FL.S2FL	25)	S1FL.S2FL
12)	V1FO.S2FH	26)	V1FO.S2FH
13)	C1FL.P5B	27)	S1FL.P5B
14)	C1FL.P6B	28)	S1FL.P6B

Table C.23: Potential causes of failure for tank level pattern increasing to full in the DORMANT operating mode after performing the coherent approximation

C.2 Success Tree Construction

C.2.1 Working High Flow in Section 1 (V1)

$$\text{SUCCESSHFV1} = \overline{\text{NWMS}}.\overline{\text{P1B}}.\overline{\text{P1F}}.\overline{\text{P2B}}.\overline{\text{V1FC}}.\overline{\text{C1FH}}.\overline{\text{S1FE}}.\overline{\text{S1FL}}.\overline{\text{S1FH}}.\overline{\text{S1FVH}}.\overline{\text{S1FF}}$$

C.2.2 Working High Flow in Section 2 (V2)

$$\text{SUCCESSHFV2} = \overline{\text{DORMANT}}.\overline{\text{V2FC}}.\overline{\text{P3B}}.\overline{\text{P3F}}.\overline{\text{P4B}}$$

C.2.3 Working High Flow in Section 3 (V3)

$$\text{SUCCESSHFV3} = \overline{\text{P5B}}.\overline{\text{P5F}}.\overline{\text{P6B}}.\overline{\text{V3FC}}.\overline{\text{C2FL}}.\overline{\text{S2FE}}.\overline{\text{S2FL}}$$

C.2.4 Working Low Flow in Section 1 (V1)

$$\text{SUCCESSLFV1} = \overline{\text{V1FO}}.\overline{\text{C1FL}}.\overline{\text{S1FE}}.\overline{\text{S1FL}}$$

C.2.5 Working Low Flow in Section 3 (V3)

$$\text{SUCCESSLFV3} = \overline{\text{V3FO}}.\overline{\text{C2FH}}.\overline{\text{S2FH}}.\overline{\text{S2FVH}}.\overline{\text{S2FF}}$$

C.2.6 Working Tray Level in Section 4

$$\text{SUCCESSTRAYL} = \overline{\text{TR}}.\overline{\text{TL}}$$

C.2.7 Normal Level Pattern

$$\mathrm{SUCCESSTANKNORMAL} = \overline{\mathrm{TR}}.\overline{\mathrm{P5F}}.\overline{\mathrm{V3FO}}.\overline{\mathrm{C2FH}}.\overline{\mathrm{S2FVH}}.\overline{\mathrm{S2FF}}$$

Appendix D

Fault and Success Trees for the Fuel Rig when ACTIVE or DORMANT

D.1 Fault Trees

D.1.1 High Flow at IVP0130

$$\begin{aligned}\mathrm{HFIVP0130} = {} & \overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121PB}}.\overline{\mathrm{P0121L}} \\ & .\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122PB}}.\overline{\mathrm{P0122L}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123PB}}\,(\mathrm{IVP0130FO} + \mathrm{CT0130T}.\overline{\mathrm{CT0130F}})\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{IVP0130FO}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121PB}}.\overline{\mathrm{P0121L}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122PB}}.\overline{\mathrm{P0122L}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123PB}}$
2)	$\mathrm{CT0130T}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121PB}}.\overline{\mathrm{P0121L}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122PB}}.\overline{\mathrm{P0122L}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123PB}}.\overline{\mathrm{CT0130F}}$

Table D.1: Prime implicants for high flow at IVP0130
in the ACTIVE or DORMANT operating modes

D.1.2 Partial Flow at IVP0130

$$\begin{aligned}\mathrm{PFIVP0130} = {} & \overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}\\ & .\{\mathrm{IVP0130S}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130FO}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{IVP0130L}}\\ & +\{\mathrm{IVP0130FO}.(\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{IVP0130L}})\\ & +\mathrm{C0130T}.(\overline{\mathrm{CT0130F}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{IVP0130L}})\}\\ & .(\mathrm{P0121PB}.\overline{\mathrm{P0121L}} + \mathrm{P0121L}.\overline{\mathrm{P0121PB}} + \mathrm{P0122PB}.\overline{\mathrm{P0122L}} + \mathrm{P0122L}.\overline{\mathrm{P0122PB}}\\ & +\mathrm{P0123PB}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123F}}.\overline{\mathrm{P0123L}})\}\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{IVP0130S}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130FO}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}$
2)	$\mathrm{P0121PB}.\mathrm{IVP0130FO}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121L}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}$
3)	$\mathrm{P0121L}.\mathrm{IVP0130FO}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121PB}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}$
4)	$\mathrm{P0122PB}.\mathrm{IVP0130FO}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122L}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}$
5)	$\mathrm{P0122L}.\mathrm{IVP0130FO}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}$
6)	$\mathrm{P0123PB}.\mathrm{IVP0130FO}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123F}}.\overline{\mathrm{P0123L}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{IVP0130S}}.\overline{\mathrm{IVP0130L}}.\overline{\mathrm{IVP0130PB}}$
7)	$\mathrm{P0121PB}.\mathrm{CT0130T}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121L}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{CT0130F}}$
8)	$\mathrm{P0121L}.\mathrm{CT0130T}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0121PB}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{CT0130F}}$
9)	$\mathrm{P0122PB}.\mathrm{CT0130T}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122L}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{CT0130F}}$
10)	$\mathrm{P0122L}.\mathrm{CT0130T}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{P0122PB}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0123B}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{CT0130F}}$
11)	$\mathrm{P0123PB}.\mathrm{CT0130T}.\overline{\mathrm{P0123B}}.\overline{\mathrm{P0123F}}.\overline{\mathrm{P0123L}}.\overline{\mathrm{P0121B}}.\overline{\mathrm{P0121F}}.\overline{\mathrm{P0122B}}.\overline{\mathrm{P0122F}}.\overline{\mathrm{IVP0130B}}.\overline{\mathrm{IVP0130FC}}.\overline{\mathrm{CT0130F}}$

Table D.2: Prime implicants for partial flow at IVP0130 when in the ACTIVE or DORMANT operating modes

D.1.3 High Flow at IVP0110

$$\begin{aligned}\mathrm{HFIVP0110} = {} & \overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0103B}}\\ & .\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}\\ & .\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}\\ & .\overline{\mathrm{PP0110L}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{BP0110PB}}.(\mathrm{IVP0110FO}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}\\ & .\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}} + \mathrm{CT0110T}.\overline{\mathrm{CT0110F}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}\\ & .\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}}).(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}} + \mathrm{DORMANT}.\mathrm{PP0110FO}.\overline{\mathrm{ACTIVE}})\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{IVP0110FO}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{BP0110PB}}$
2)	$\mathrm{CT0110T}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{CT0110F}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{BP0110PB}}$

Table D.3: Prime implicants for high flow at IVP0110 when in the ACTIVE operating mode

Number	Prime Implicants
1)	IVP0110FO.PP0110FO.IVP0110FC.IVP0110B.IVP0110PB.IVP0110S.IVP0110L.P0101B.P0101F.P0101PB .P0101L.P0102B.P0102F.P0102PB.P0102L.P0103B.P0103F.P0103PB.P0103L.P0104B.P0104F .P0104PB.P0104L.P0105B.P0105PB.P0106B.P0106PB.P0113B.P0113PB.P0114B.P0114PB .PP0110FSO.PP0110FM.PP0110L.BP0110B.BP0110PB
2)	CT0110T.PP0110FO.IVP0110FC.IVP0110B.IVP0110PB.IVP0110S.IVP0110L.P0101B.P0101F.P0101PB .P0101L.P0102B.P0102F.P0102PB.P0102L.P0103B.P0103F.P0103PB.P0103L.P0104B.P0104F .P0104PB.P0104L.P0105B.P0105PB.P0106B.P0106PB.P0113B.P0113PB.P0114B.P0114PB .PP0110FSO.PP0110FM.PP0110L.CT0110F.BP0110B.BP0110PB

Table D.4: Prime implicants for high flow at IVP0110 when in the DORMANT operating mode

D.1.4 High Flow at IVP0120

$$\begin{aligned}\mathrm{HFIVP0120} = {} & \overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}}.\overline{\mathrm{P0108B}} \\ & .\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111PB}} \\ & .\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}} \\ & .\overline{\mathrm{PP0120L}}.\overline{\mathrm{BP0120B}}.\overline{\mathrm{BP0120PB}}.(\mathrm{IVP0120FO}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120S}} \\ & .\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}} + \mathrm{CT0120T}.\overline{\mathrm{CT0120F}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120S}} \\ & .\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}}).(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}} + \mathrm{DORMANT}.\mathrm{PP0120FO}.\overline{\mathrm{ACTIVE}})\end{aligned}$$

Number	Prime Implicants
1)	IVP0120FO.IVP0120FC.IVP0120B.IVP0120PB.IVP0120S.IVP0120L.P0107B.P0107F.P0107PB .P0107L.P0108B.P0108F.P0108PB.P0108L.P0109B.P0109F.P0109PB.P0109L.P0110B.P0110F .P0110PB.P0110L.P0111B.P0111PB.P0112B.P0112PB.P0113B.P0113PB.P0114B.P0114PB .PP0120FSO.PP0120FM.PP0120L.BP0120B.BP0120PB
2)	CT0120T.IVP0120FC.IVP0120B.IVP0120PB.IVP0120S.IVP0120L.P0107B.P0107F.P0107PB .P0107L.P0108B.P0108F.P0108PB.P0108L.P0109B.P0109F.P0109PB.P0109L.P0110B.P0110F .P0110PB.P0110L.P0111B.P0111PB.P0112B.P0112PB.P0113B.P0113PB.P0114B.P0114PB .PP0120FSO.PP0120FM.PP0120L.CT0120F.BP0120B.BP0120PB

Table D.5: Prime implicants for high flow at IVP0120 when in the ACTIVE operating mode

Number	Prime Implicants
1)	IVP0120FO.PP0120FO.IVP0120FC.IVP0120B.IVP0120PB.IVP0120S.IVP0120L.P0107B.P0107F.P0107PB .P0107L.P0108B.P0108F.P0108PB.P0108L.P0109B.P0109F.P0109PB.P0109L.P0110B.P0110F .P0110PB.P0110L.P0111B.P0111PB.P0112B.P0112PB.P0113B.P0113PB.P0114B.P0114PB .PP0120FSO.PP0120FM.PP0120L.BP0120B.BP0120PB
2)	CT0120T.PP0120FO.IVP0120FC.IVP0120B.IVP0120PB.IVP0120S.IVP0120L.P0107B.P0107F.P0107PB .P0107L.P0108B.P0108F.P0108PB.P0108L.P0109B.P0109F.P0109PB.P0109L.P0110B.P0110F .P0110PB.P0110L.P0111B.P0111PB.P0112B.P0112PB.P0113B.P0113PB.P0114B.P0114PB .PP0120FSO.PP0120FM.PP0120L.CT0120F.BP0120B.BP0120PB

Table D.6: Prime implicants for high flow at IVP0120 when in the DORMANT operating mode

D.1.5 Low Flow at IVP0110

$$\begin{aligned}\mathrm{LFIVP0110} = {} & \mathrm{P0101B}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}} + \mathrm{P0101F}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}} \\ & + \mathrm{P0102B}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}} + \mathrm{P0102F}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}} \\ & + \mathrm{P0103B}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}} + \mathrm{P0103F}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}} \\ & + \mathrm{P0104B}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}} + \mathrm{P0104F}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}} \\ & + \mathrm{P0105B}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0105L}} + \mathrm{P0106B}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0106L}} \\ & + \mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}} + \mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}} \\ & + \mathrm{IVP0110FC}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}} \\ & + \mathrm{IVP0110B}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}} \\ & + \mathrm{CT0110F}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}} + \mathrm{BP0110B}.\overline{\mathrm{BP0110PB}}.\overline{\mathrm{BP0110L}} \\ & + \mathrm{PP0110FSO}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{P0101B}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}$
2)	$\mathrm{P0101F}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}$
3)	$\mathrm{P0102B}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}$
4)	$\mathrm{P0102F}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}$
5)	$\mathrm{P0103B}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}$
6)	$\mathrm{P0103F}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}$
7)	$\mathrm{P0104B}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}}$
8)	$\mathrm{P0104F}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}}$
9)	$\mathrm{P0105B}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0105L}}$
10)	$\mathrm{P0106B}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0106L}}$
11)	$\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}$
12)	$\mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}}$
13)	$\mathrm{IVP0110FC}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}}$
14)	$\mathrm{IVP0110B}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}}$
15)	$\mathrm{CT0110F}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{CT0110T}}$
16)	$\mathrm{BP0110B}.\overline{\mathrm{BP0110PB}}.\overline{\mathrm{BP0110L}}$
17)	$\mathrm{PP0110FSO}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}$

Table D.7: Prime implicants for low flow at IVP0110 when in the ACTIVE operating mode

D.1.6 Low Flow at IVP0120

$$\begin{aligned}\mathrm{PFIVP0120NF} = {} & \mathrm{P0107B}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}} + \mathrm{P0107F}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}} \\ & + \mathrm{P0108B}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}} + \mathrm{P0108F}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}} \\ & + \mathrm{P0109B}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}} + \mathrm{P0109F}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}} \\ & + \mathrm{P0110B}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}} + \mathrm{P0110F}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}} \\ & + \mathrm{P0111B}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111PB}}.\overline{\mathrm{P0111L}} + \mathrm{P0112B}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0112L}} \\ & + \mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}} + \mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}} \\ & + \mathrm{IVP0120FC}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}} \\ & + \mathrm{IVP0120B}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}} \\ & + \mathrm{CT0120F}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120S}} + \mathrm{BP0120B}.\overline{\mathrm{BP0120PB}}.\overline{\mathrm{BP0120L}} \\ & + \mathrm{PP0120FSO}.\overline{\mathrm{PP0120FM}}.\overline{\mathrm{PP0120L}}\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{P0107B}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}$
2)	$\mathrm{P0107F}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}$
3)	$\mathrm{P0108B}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}}$
4)	$\mathrm{P0108F}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}}$
5)	$\mathrm{P0109B}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}}$
6)	$\mathrm{P0109F}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}}$
7)	$\mathrm{P0110B}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}}$
8)	$\mathrm{P0110F}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}}$
9)	$\mathrm{P0111B}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111PB}}.\overline{\mathrm{P0111L}}$
10)	$\mathrm{P0112B}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0112L}}$
11)	$\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}$
12)	$\mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}}$
13)	$\mathrm{IVP0120FC}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}}$
14)	$\mathrm{IVP0120B}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120L}}$
15)	$\mathrm{CT0120F}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{CT0120T}}$
16)	$\mathrm{BP0120B}.\overline{\mathrm{BP0120PB}}.\overline{\mathrm{BP0120L}}$
17)	$\mathrm{PP0120FSO}.\overline{\mathrm{PP0120FO}}.\overline{\mathrm{PP0120FM}}.\overline{\mathrm{PP0120L}}$

Table D.8: Prime implicants for low flow at IVP0120 when in the ACTIVE operating mode

D.1.7 Partial Flow at IVP0110 when Flow is Required

$$\begin{aligned}\mathrm{PFIVP0110F} = {} & \overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}} \\ & .\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}.(\mathrm{P0101PB}.\overline{\mathrm{P0101L}} + \mathrm{P0101L}.\overline{\mathrm{P0101PB}} \\ & + \mathrm{P0102PB}.\overline{\mathrm{P0102L}} + \mathrm{P0102L}.\overline{\mathrm{P0102PB}} + \mathrm{P0103PB}.\overline{\mathrm{P0103L}} + \mathrm{P0103L}.\overline{\mathrm{P0103PB}} + \mathrm{P0104PB}.\overline{\mathrm{P0104L}} \\ & + \mathrm{P0104L}.\overline{\mathrm{P0104PB}} + \mathrm{P0105PB}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105L}} + \mathrm{P0106PB}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106L}} + \mathrm{P0113PB}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113L}} \\ & + \mathrm{P0114PB}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114L}} + \mathrm{IVP0110S}.\overline{\mathrm{IVP010FO}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}} \\ & + \mathrm{IVP0110PB}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}} + \mathrm{IVP0110L}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}} \\ & + \mathrm{BP0110PB}.\overline{\mathrm{BP0110L}} + \mathrm{PP0110FM}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110L}} + \mathrm{PP0110L}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FM}})\end{aligned}$$

Number	Prime Implicants
1)	$\mathrm{P0101PB}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
2)	$\mathrm{P0101L}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
3)	$\mathrm{P0102PB}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
4)	$\mathrm{P0102L}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
5)	$\mathrm{P0103PB}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
6)	$\mathrm{P0103L}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
7)	$\mathrm{P0104PB}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
8)	$\mathrm{P0104L}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
9)	$\mathrm{P0105PB}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$
10)	$\mathrm{P0106PB}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110F}}$

Table D.9: Prime implicants for partial flow at IVP0110 when flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
11)	$P0113PB.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}$
12)	$P0114PB.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}$
13)	$IVP0110S.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{PP0110FSO}.\overline{CT0110F}$
14)	$IVP0110PB.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{IVP0110L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{PP0110FSO}.\overline{CT0110F}$
15)	$IVP0110L.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{PP0110FSO}.\overline{CT0110F}$
16)	$BP0110PB.\overline{BP0110B}.\overline{BP0110L}.\overline{PP0110FSO}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}$
17)	$PP0110FM.\overline{PP0110FO}.\overline{PP0110FSO}.\overline{PP0110L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}$
18)	$PP0110L.\overline{PP0110FO}.\overline{PP0110FM}.\overline{PP0110FSO}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}$

Table D.10: Prime implicants for partial flow at IVP0110 when flow is required in the ACTIVE operating mode - Table 2

D.1.8 Partial Flow at IVP0120 when Flow is Required

$$
\begin{aligned}
PFIVP0120F = {} & \overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B} \\
& .\overline{IVP0120B}.\overline{IVP0120FC}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.(P0107PB.\overline{P0107L} + P0107L.\overline{P0107PB} \\
& +P0108PB.\overline{P0108L} + P0108L.\overline{P0108PB} + P0109PB.\overline{P0109L} + P0109L.\overline{P0109PB} + P0110PB.\overline{P0110L} \\
& +P0110L.\overline{P0110PB} + P0111PB.\overline{P0111F}.\overline{P0111L} + P0112PB.\overline{P0112F}.\overline{P0112L} + P0113PB.\overline{P0113F}.\overline{P0113L} \\
& +P0114PB.\overline{P0114F}.\overline{P0114L} + IVP0120S.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +IVP0120PB.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120L} + IVP0120L.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120PB} \\
& +BP0120PB.\overline{BP0120L} + PP0120FM.\overline{PP0120FO}.\overline{PP0120L} + PP0120L.\overline{PP0120FO}.\overline{PP0120FM})
\end{aligned}
$$

Number	Prime Implicants
1)	$P0107PB.\overline{P0107B}.\overline{P0107F}.\overline{P0107L}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
2)	$P0107L.\overline{P0107B}.\overline{P0107F}.\overline{P0107PB}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
3)	$P0108PB.\overline{P0108B}.\overline{P0108F}.\overline{P0108L}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
4)	$P0108L.\overline{P0108B}.\overline{P0108F}.\overline{P0108PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
5)	$P0109PB.\overline{P0109B}.\overline{P0109F}.\overline{P0109L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
6)	$P0109L.\overline{P0109B}.\overline{P0109F}.\overline{P0109PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
7)	$P0110PB.\overline{P0110B}.\overline{P0110F}.\overline{P0110L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
8)	$P0110L.\overline{P0110B}.\overline{P0110F}.\overline{P0110PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
9)	$P0111PB.\overline{P0111B}.\overline{P0111F}.\overline{P0111L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
10)	$P0112PB.\overline{P0112B}.\overline{P0112F}.\overline{P0112L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
11)	$P0113PB.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$

Table D.11: Prime implicants for partial flow at IVP0120 when flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
12)	P0114PB.$\overline{P0114B}.\overline{P0114F}.\overline{P0114L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
13)	IVP0120S.$\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
14)	IVP0120PB.$\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
15)	IVP0120L.$\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
15)	IVP0120L.$\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
16)	BP0120PB.$\overline{BP0120B}.\overline{BP0120L}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}$
17)	PP0120FM.$\overline{PP0120FO}.\overline{PP0120FSO}.\overline{PP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}$
18)	PP0120L.$\overline{PP0120FO}.\overline{PP0120FM}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}$

Table D.12: Prime implicants for partial flow at IVP0120 when flow is required in the ACTIVE operating mode - Table 2

D.1.9 Partial Flow at IVP0110 when Low Flow is Required

$$
\begin{aligned}
\mathrm{PFIVP0110LF} = {} & \overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B} \\
& .\overline{IVP0110B}.\overline{IVP0110FC}.\overline{BP0110B}.\overline{PP0110FSO}.(ACTIVE.\overline{DORMANT} \\
& +DORMANT.PP0110FO.\overline{ACTIVE}.\overline{PP0110FM}.\overline{PP0110L}).\{(P0101PB.\overline{P0101L} + P0101L.\overline{P0101PB} \\
& +P0102PB.\overline{P0102L} + P0102L.\overline{P0102PB} + P0103PB.\overline{P0103L} + P0103L.\overline{P0103PB} + P0104PB.\overline{P0104L} \\
& +P0104L.\overline{P0104PB} + P0105PB.\overline{P0105F}.\overline{P0105L} + P0106PB.\overline{P0106F}.\overline{P0106L} + P0113PB.\overline{P0113F}.\overline{P0113L} \\
& +P0114PB.\overline{P0114F}.\overline{P0114L} + BP0110PB.\overline{BP0110L} + PP0110FM.\overline{PP0110FO}.\overline{PP0110L} \\
& +PP0110L.\overline{PP0110FO}.\overline{PP0110FM}).(IVP0110FO.\overline{IVP0110S}.\overline{IVP0110L}.\overline{IVP0110PB} \\
& +CT0110T.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110L}.\overline{IVP0110PB}) + IVP0110S.\overline{IVP010FO}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +IVP0110PB.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{IVP0110L} + IVP0110L.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{IVP0110PB}\}
\end{aligned}
$$

Number	Prime Implicants
1)	P0101PB.IVP0110FO.$\overline{P0101B}.\overline{P0101F}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
2)	P0101L.IVP0110FO.$\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
3)	P0102PB.IVP0110FO.$\overline{P0102B}.\overline{P0102F}.\overline{P0102L}.\overline{P0101B}.\overline{P0101F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
4)	P0102L.IVP0110FO.$\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
5)	P0103PB.IVP0110FO.$\overline{P0103B}.\overline{P0103F}.\overline{P0103L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
6)	P0103L.IVP0110FO.$\overline{P0103B}.\overline{P0103F}.\overline{P0103PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
7)	P0104PB.IVP0110FO.$\overline{P0104B}.\overline{P0104F}.\overline{P0104L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
8)	P0104L.IVP0110FO.$\overline{P0104B}.\overline{P0104F}.\overline{P0104PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0105B}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
9)	P0105PB.IVP0110FO.$\overline{P0105B}.\overline{P0105F}.\overline{P0105L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$
10)	P0106PB.IVP0110FO.$\overline{P0106B}.\overline{P0106F}.\overline{P0106L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}$

Table D.13: Prime implicants for partial flow at IVP0110 when low flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
11)	P0113PB.IVP0110FO.$\overline{P0113B}$.$\overline{P0113F}$.$\overline{P0113L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$
12)	P0114PB.IVP0110FO.$\overline{P0114B}$.$\overline{P0114F}$.$\overline{P0114L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$
13)	BP0110PB.IVP0110FO.$\overline{BP0110B}$.$\overline{BP0110L}$.$\overline{PP0110FSO}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$
14)	PP0110FM.IVP0110FO.$\overline{PP0110FO}$.$\overline{PP0110FSO}$.$\overline{PP0110L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$
15)	PP0110L.IVP0110FO.$\overline{PP0110FO}$.$\overline{PP0110FM}$.$\overline{PP0110FSO}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$
16)	P0101PB.CT0110T.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0101L}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
17)	P0101L.CT0110T.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0101PB}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
18)	P0102PB.CT0110T.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0102L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
19)	P0102L.CT0110T.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0102PB}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
20)	P0103PB.CT0110T.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0103L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
21)	P0103L.CT0110T.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0103PB}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
22)	P0104PB.CT0110T.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0104L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
23)	P0104L.CT0110T.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0104PB}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
24)	P0105PB.CT0110T.$\overline{P0105B}$.$\overline{P0105F}$.$\overline{P0105L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
25)	P0106PB.CT0110T.$\overline{P0106B}$.$\overline{P0106F}$.$\overline{P0106L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
26)	P0113PB.CT0110T.$\overline{P0113B}$.$\overline{P0113F}$.$\overline{P0113L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
27)	P0114PB.CT0110T.$\overline{P0114B}$.$\overline{P0114F}$.$\overline{P0114L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
28)	BP0110PB.CT0110T.$\overline{BP0110B}$.$\overline{BP0110L}$.$\overline{PP0110FSO}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{CT0110F}$
29)	PP0110FM.CT0110T.$\overline{PP0110FO}$.$\overline{PP0110FSO}$.$\overline{PP0110L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{CT0110F}$
30)	PP0110L.CT0110T.$\overline{PP0110FO}$.$\overline{PP0110FM}$.$\overline{PP0110FSO}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{CT0110F}$
31)	IVP0110S.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110FO}$.$\overline{IVP0110L}$.$\overline{IVP0110PB}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
32)	IVP0110PB.CT0110T.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110FO}$.$\overline{IVP0110L}$.$\overline{IVP0110S}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$
33)	IVP0110L.CT0110T.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{IVP0110FO}$.$\overline{IVP0110PB}$.$\overline{IVP0110S}$.$\overline{PP0110FSO}$.$\overline{CT0110F}$

Table D.14: Prime implicants for partial flow at IVP0110 when low flow is required in the ACTIVE operating mode - Table 2

Number	Prime Implicants
1)	P0101PB.IVP0110FO.PP0110FO.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0101L}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$
2)	P0101L.IVP0110FO.PP0110FO.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0101PB}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$
3)	P0102PB.IVP0110FO.PP0110FO.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0102L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$
4)	P0102L.IVP0110FO.PP0110FO.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0102PB}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$
5)	P0103PB.IVP0110FO.PP0110FO.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0103L}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$
6)	P0103L.IVP0110FO.PP0110FO.$\overline{P0103B}$.$\overline{P0103F}$.$\overline{P0103PB}$.$\overline{P0101B}$.$\overline{P0101F}$.$\overline{P0102B}$.$\overline{P0102F}$.$\overline{P0104B}$.$\overline{P0104F}$.$\overline{P0105B}$.$\overline{P0106B}$.$\overline{P0113B}$.$\overline{P0114B}$.$\overline{BP0110B}$.$\overline{IVP0110FC}$.$\overline{IVP0110B}$.$\overline{PP0110FSO}$.$\overline{IVP0110S}$.$\overline{IVP0110PB}$.$\overline{IVP0110L}$.$\overline{PP0110L}$.$\overline{PP0110FM}$

Table D.15: Prime implicants for partial flow at IVP0110 when low flow is required in the DORMANT operating mode - Table 1

Number	Prime Implicants
7)	P0104PB.IVP0110FO.PP0110FO.P0104B.P0104F.P0104L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
8)	P0104L.IVP0110FO.PP0110FO.P0104B.P0104F.P0104PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
9)	P0105PB.IVP0110FO.PP0110FO.P0105B.P0105F.P0105L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
10)	P0106PB.IVP0110FO.PP0110FO.P0106B.P0106F.P0106L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
11)	P0113PB.IVP0110FO.PP0110FO.P0113B.P0113F.P0113L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0106B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
12)	P0114PB.IVP0110FO.PP0110FO.P0114B.P0114F.P0114L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0106B.P0113B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
13)	BP0110PB.IVP0110FO.PP0110FO.BP0110B.BP0110L.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.IVP0110FC.IVP0110B.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
14)	PP0110FM.IVP0110FO.PP0110FO.PP0110FO.PP0110FSO.PP0110L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
15)	PP0110L.IVP0110FO.PP0110FO.PP0110FO.PP0110FM.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.IVP0110S.IVP0110PB.IVP0110L.PP0110L.PP0110FM
16)	P0101PB.CT0110T.PP0110FO.P0101B.P0101F.P0101L.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
17)	P0101L.CT0110T.PP0110FO.P0101B.P0101F.P0101PB.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
18)	P0102PB.CT0110T.PP0110FO.P0102B.P0102F.P0102L.P0101B.P0101F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
19)	P0102L.CT0110T.PP0110FO.P0102B.P0102F.P0102PB.P0101B.P0101F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
20)	P0103PB.CT0110T.PP0110FO.P0103B.P0103F.P0103L.P0101B.P0101F.P0102B.P0102F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
21)	P0103L.CT0110T.PP0110FO.P0103B.P0103F.P0103PB.P0101B.P0101F.P0102B.P0102F.P0104B.P0104F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
22)	P0104PB.CT0110T.PP0110FO.P0104B.P0104F.P0104L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
23)	P0104L.CT0110T.PP0110FO.P0104B.P0104F.P0104PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0106B .P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
24)	P0105PB.CT0110T.PP0110FO.P0105B.P0105F.P0105L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
25)	P0106PB.CT0110T.PP0110FO.P0106B.P0106F.P0106L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
26)	P0113PB.CT0110T.PP0110FO.P0113B.P0113F.P0113L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0106B.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
27)	P0114PB.CT0110T.PP0110FO.P0114B.P0114F.P0114L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0106B.P0113B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.PP0110L.PP0110FM
28)	BP0110PB.CT0110T.PP0110FO.BP0110B.BP0110L.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.IVP0110FC.IVP0110B.CT0110F.PP0110L.PP0110FM
29)	PP0110FM.CT0110T.PP0110FO.PP0110FO.PP0110FSO.PP0110L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.CT0110F.PP0110L.PP0110FM
30)	PP0110L.CT0110T.PP0110FO.PP0110FO.PP0110FM.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0106B.P0113B.P0114B.BP0110B.IVP0110FC.IVP0110B.CT0110F.PP0110L.PP0110FM
31)	IVP0110S-PP0110FO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B.P0113B .P0114B.BP0110B.IVP0110FC.IVP0110B.IVP0110FO.IVP0110L.IVP0110PB.PP0110FSO.CT0110F.PP0110L.PP0110FM
32)	IVP0110PB.CT0110T.PP0110FO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B.P0113B .P0114B.BP0110B.IVP0110FC.IVP0110B.IVP0110FO.IVP0110L.IVP0110S.PP0110FSO.CT0110F.PP0110L.PP0110FM
33)	IVP0110L.CT0110T.PP0110FO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0106B.P0113B .P0114B.BP0110B.IVP0110FC.IVP0110B.IVP0110FO.IVP0110PB.IVP0110S.PP0110FSO.CT0110F.PP0110L.PP0110FM

Table D.16: Prime implicants for partial flow at IVP0110 when low flow is required in the DORMANT operating mode - Table 2

D.1.10 Partial Flow at IVP0120 when Low Flow is Required

$$
\begin{aligned}
PFIVP0120LF = {} & \overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B} \\
& .\overline{IVP0120B}.\overline{IVP0120FC}.\overline{BP0120B}.\overline{PP0120FSO}.(ACTIVE.\overline{DORMANT} \\
& + DORMANT.PP0120FO.\overline{ACTIVE}.\overline{PP0120FM}.\overline{PP0120L}).\{(P0107PB.\overline{P0107L} + P0107L.\overline{P0107PB} \\
& + P0102PB.\overline{P0108L} + P0108L.\overline{P0108PB} + P0109PB.\overline{P0109L} + P0109L.\overline{P0109PB} + P0110PB.\overline{P0110L} \\
& + P0110L.\overline{P0110PB} + P0115PB.\overline{P0111F}.\overline{P0111L} + P0116PB.\overline{P0112F}.\overline{P0112L} + P0113PB.\overline{P0113F}.\overline{P0113L} \\
& + P0114PB.\overline{P0114F}.\overline{P0114L} + BP0120PB.\overline{BP0120L} + PP0120FM.\overline{PP0120FO}.\overline{PP0120L} \\
& + PP0120L.\overline{PP0120FO}.\overline{PP0120FM}).(IVP0120FO.\overline{IVP0120S}.\overline{IVP0120L}.\overline{IVP0120PB} \\
& + CT0120T.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120L}.\overline{IVP0120PB}) + IVP0120S.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& + IVP0120PB.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120L} + IVP0120L.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120PB}\}
\end{aligned}
$$

Number	Prime Implicants
1)	$P0107PB.IVP0120FO.\overline{P0107B}.\overline{P0107F}.\overline{P0107L}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
2)	$P0107L.IVP0120FO.\overline{P0107B}.\overline{P0107F}.\overline{P0107PB}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
3)	$P0108PB.IVP0120FO.\overline{P0108B}.\overline{P0108F}.\overline{P0108L}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
4)	$P0108L.IVP0120FO.\overline{P0108B}.\overline{P0108F}.\overline{P0108PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
5)	$P0109PB.IVP0120FO.\overline{P0109B}.\overline{P0109F}.\overline{P0109L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
6)	$P0109L.IVP0120FO.\overline{P0109B}.\overline{P0109F}.\overline{P0109PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
7)	$P0110PB.IVP0120FO.\overline{P0110B}.\overline{P0110F}.\overline{P0110L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
8)	$P0110L.IVP0120FO.\overline{P0110B}.\overline{P0110F}.\overline{P0110PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
9)	$P0111PB.IVP0120FO.\overline{P0111B}.\overline{P0111F}.\overline{P0111L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
10)	$P0112PB.IVP0120FO.\overline{P0112B}.\overline{P0112F}.\overline{P0112L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
11)	$P0113PB.IVP0120FO.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
12)	$P0114PB.IVP0120FO.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
13)	$BP0120PB.IVP0120FO.\overline{BP0120B}.\overline{BP0120L}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
14)	$PP0120FM.IVP0120FO.\overline{PP0120FO}.\overline{PP0120FSO}.\overline{PP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
15)	$PP0120L.IVP0120FO.\overline{PP0120FO}.\overline{PP0120FM}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
16)	$P0107PB.CT0120T.\overline{P0107B}.\overline{P0107F}.\overline{P0107L}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
17)	$P0107L.CT0120T.\overline{P0107B}.\overline{P0107F}.\overline{P0107PB}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
18)	$P0108PB.CT0120T.\overline{P0108B}.\overline{P0108F}.\overline{P0108L}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
19)	$P0108L.CT0120T.\overline{P0108B}.\overline{P0108F}.\overline{P0108PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
20)	$P0109PB.CT0120T.\overline{P0109B}.\overline{P0109F}.\overline{P0109L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
21)	$P0109L.CT0120T.\overline{P0109B}.\overline{P0109F}.\overline{P0109PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
22)	$P0110PB.CT0120T.\overline{P0110B}.\overline{P0110F}.\overline{P0110L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$
23)	$P0110L.CT0120T.\overline{P0110B}.\overline{P0110F}.\overline{P0110PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}$

Table D.17: Prime implicants for partial flow at IVP0120 when low flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
24)	P0111PB.CT0120T.P0111B.P0111F.P0111L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F
25)	P0112PB.CT0120T.P0112B.P0112F.P0112L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F
26)	P0113PB.CT0120T.P0113B.P0113F.P0113L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F
27)	P0114PB.CT0120T.P0114B.P0114F.P0114L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F
28)	BP0120PB.CT0120T.BP0120B.BP0120L.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.IVP0120FC.IVP0120B.CT0120F
29)	PP0120FM.CT0120T.PP0120FO.PP0120FSO.PP0120L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.CT0120F
30)	PP0120L.CT0120T.PP0120FO.PP0120FM.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.CT0120F
31)	IVP0120S.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.IVP0120FO.IVP0120L.PP0120FSO.CT0120F
32)	IVP0120PB.CT0120T.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.IVP0120FO.IVP0120L.IVP0120S.PP0120FSO.CT0120F
33)	IVP0120L.CT0120T.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.IVP0120FO.IVP0120PB.IVP0120S.PP0120FSO.CT0120F

Table D.18: Prime implicants for partial flow at IVP0120 when low flow is required in the ACTIVE operating mode - Table 2

Number	Prime Implicants
1)	P0107PB.IVP0120FO.PP0120FO.P0101B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
2)	P0107L.IVP0120FO.PP0120FO.P0107B.P0107F.P0107PB.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
3)	P0108PB.IVP0120FO.PP0120FO.P0108B.P0108F.P0108L.P0107B.P0107F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
4)	P0108L.IVP0120FO.PP0120FO.P0108B.P0108F.P0108PB.P0107B.P0107F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
5)	P0109PB.IVP0120FO.PP0120FO.P0109B.P0109F.P0109L.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
6)	P0109L.IVP0120FO.PP0120FO.P0109B.P0109F.P0109PB.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
7)	P0110PB.IVP0120FO.PP0120FO.P0110B.P0110F.P0110L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
8)	P0110L.IVP0120FO.PP0120FO.P0110B.P0110F.P0110PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
9)	P0111PB.IVP0120FO.PP0120FO.P0111B.P0111F.P0111L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
10)	P0112PB.IVP0120FO.PP0120FO.P0112B.P0112F.P0112L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
11)	P0113PB.IVP0120FO.PP0120FO.P0113B.P0113F.P0113L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
12)	P0114PB.IVP0120FO.PP0120FO.P0114B.P0114F.P0114L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
13)	BP0120PB.IVP0120FO.PP0120FO.BP0120B.BP0120L.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.IVP0120FC.IVP0120B.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
14)	PP0120FM.IVP0120FO.PP0120FO.PP0120FO.PP0120FSO.PP0120L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0104F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
15)	PP0120L.IVP0120FO.PP0120FO.PP0120FO.PP0120FM.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.IVP0120S.IVP0120PB.IVP0120L.PP0120L.PP0120FM
16)	P0107PB.CT0120T.PP0120FO.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.PP0120L.PP0120FM
17)	P0107L.CT0120T.PP0120FO.P0107B.P0107F.P0107PB.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.PP0120L.PP0120FM
18)	P0108PB.CT0120T.PP0120FO.P0108B.P0108F.P0108L.P0107B.P0107F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.PP0120L.PP0120FM
19)	P0108L.CT0120T.PP0120FO.P0108B.P0108F.P0108PB.P0107B.P0107F.P0109B.P0109F.P0110B.P0110F.P0111B.P0112B.P0113B.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.PP0120L.PP0120FM

Table D.19: Prime implicants for partial flow at IVP0120 when low flow is required in the DORMANT operating mode - Table 1

Number	Prime Implicants
20)	$P0109PB.CT0120T.PP0120FO.\overline{P0109B}.\overline{P0109F}.\overline{P0109L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
21)	$P0109L.CT0120T.PP0120FO.\overline{P0109B}.\overline{P0109F}.\overline{P0109PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
22)	$P0110PB.CT0120T.PP0120FO.\overline{P0110B}.\overline{P0110F}.\overline{P0110L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
23)	$P0110L.CT0120T.PP0120FO.\overline{P0110B}.\overline{P0110F}.\overline{P0110PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
24)	$P0111PB.CT0120T.PP0120FO.\overline{P0111B}.\overline{P0111F}.\overline{P0111L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0106B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
25)	$P0112PB.CT0120T.PP0120FO.\overline{P0112B}.\overline{P0112F}.\overline{P0112L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0105B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
26)	$P0113PB.CT0120T.PP0120FO.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0105B}.\overline{P0112B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
27)	$P0114PB.CT0120T.PP0120FO.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0105B}.\overline{P0112B}.\overline{P0113B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
28)	$BP0120PB.CT0120T.PP0120FO.\overline{BP0120B}.\overline{BP0120L}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
29)	$PP0120FM.CT0120T.PP0120FO.\overline{PP0120FO}.\overline{PP0120FSO}.\overline{PP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0104F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
30)	$PP0120L.CT0120T.PP0120FO.\overline{PP0120FO}.\overline{PP0120FM}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
31)	$IVP0120S.PP0120FO.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120L}.\overline{IVP0120PB}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
32)	$IVP0120PB.CT0120T.PP0120FO.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120L}.\overline{IVP0120S}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$
33)	$IVP0120L.CT0120T.PP0120FO.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0112B}.\overline{P0113B}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120L}.\overline{PP0120FM}$

Table D.20: Prime implicants for partial flow at IVP0120 when low flow is required in the DORMANT operating mode - Table 2

D.1.11 High Flow on Main Outflow Line

$$
\begin{aligned}
HFOUTFLOWF = \; & \{\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}.\overline{P0103B} \\
& .\overline{P0103F}.\overline{P0103PB}.\overline{P0103L}.\overline{P0104B}.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L}.\overline{P0105B}.\overline{P0105PB} \\
& .\overline{P0106B}.\overline{P0106PB}.\overline{P0113B}.\overline{P0113PB}.\overline{P0114B}.\overline{P0114PB}.\overline{PP0110FSO}.\overline{PP0110FM} \\
& .\overline{PP0110L}.\overline{BP0110B}.\overline{BP0110PB}.(IVP0110FO.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110S} \\
& .\overline{IVP0110PB}.\overline{IVP0110L} + CT0110T.\overline{CT0110F}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110S} \\
& .\overline{IVP0110PB}.\overline{IVP0110L}).(ACTIVE.\overline{DORMANT} + DORMANT.PP0110FO.\overline{ACTIVE})\} \\
& +\{\overline{P0107B}.\overline{P0107F}.\overline{P0107PB}.\overline{P0107L}.\overline{P0108B}.\overline{P0108F}.\overline{P0108PB}.\overline{P0108L}.\overline{P0108B} \\
& .\overline{P0109F}.\overline{P0109PB}.\overline{P0109L}.\overline{P0110B}.\overline{P0110F}.\overline{P0110PB}.\overline{P0110L}.\overline{P0111B}.\overline{P0111PB} \\
& .\overline{P0112B}.\overline{P0112PB}.\overline{P0113B}.\overline{P0113PB}.\overline{P0114B}.\overline{P0114PB}.\overline{PP0120FSO}.\overline{PP0120FM} \\
& .\overline{PP0120L}.\overline{BP0120B}.\overline{BP0120PB}.(IVP0120FO.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120S} \\
& .\overline{IVP0120PB}.\overline{IVP0120L} + CT0120T.\overline{CT0120F}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120S} \\
& .\overline{IVP0120PB}.\overline{IVP0120L}).(ACTIVE.\overline{DORMANT} + DORMANT.PP0120FO.\overline{ACTIVE})\}
\end{aligned}
$$

Number	Prime Implicants
1)	IVP0110FO.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110L}}$
2)	CT0110T.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110L}}$.$\overline{\text{CT0110F}}$
3)	IVP0120FO.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0109L}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110F}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0110L}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111F}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0111L}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112F}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0112L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$.$\overline{\text{BP0120B}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120L}}$
4)	CT0120T.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0109L}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110F}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0110L}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111F}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0111L}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112F}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0112L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$.$\overline{\text{BP0120B}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120L}}$.$\overline{\text{CT0120F}}$

Table D.21: Prime implicants for high flow on the main outflow line when low flow is required in the ACTIVE operating mode

Number	Prime Implicants
1)	IVP0110FO.PP0110FO.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$.$\overline{\text{BP0110B}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110L}}$
2)	CT0110T.PP0110FO.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110L}}$.$\overline{\text{CT0110F}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$
3)	IVP0120FO.PP0120FO.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0109L}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110F}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0110L}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111F}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0111L}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112F}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0112L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$.$\overline{\text{BP0120B}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120L}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$
4)	CT0120T.PP0120FO.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0109L}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110F}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0110L}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111F}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0111L}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112F}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0112L}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$.$\overline{\text{BP0120B}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120L}}$.$\overline{\text{CT0120F}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$

Table D.22: Prime implicants for high flow on the main outflow line when in the DORMANT operating mode

D.1.12 Low Flow on Main Outflow Line

$$\begin{aligned}
\text{LFOUTFLOW} = {} & P0113B.\overline{P0113F}.\overline{P0113PB}.\overline{P0113L} + P0113F.\overline{P0113B}.\overline{P0113PB}.\overline{P0113L} \\
& +P0114B.\overline{P0114F}.\overline{P0114PB}.\overline{P0114L} + P0114F.\overline{P0114B}.\overline{P0114PB}.\overline{P0114L} \\
& +(P0101B.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L} + P0101F.\overline{P0101B}.\overline{P0101PB}.\overline{P0101L} \\
& +P0102B.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L} + P0102F.\overline{P0102B}.\overline{P0102PB}.\overline{P0102L} \\
& +P0103B.\overline{P0103F}.\overline{P0103PB}.\overline{P0103L} + P0103F.\overline{P0103B}.\overline{P0103PB}.\overline{P0103L} \\
& +P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L} + P0104F.\overline{P0104B}.\overline{P0104PB}.\overline{P0104L} \\
& +P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L} + P0105F.\overline{P0105B}.\overline{P0105PB}.\overline{P0105L} \\
& +P0106B.\overline{P0106F}.\overline{P0106PB}.\overline{P0106L} + P0106F.\overline{P0106B}.\overline{P0106PB}.\overline{P0106L} \\
& +IVP0110FC.\overline{IVP0110FO}.\overline{IVP0110B}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +IVP0110B.\overline{IVP0110FO}.\overline{IVP0110FC}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +CT0110F.\overline{CT0110T}.\overline{IVP0110FO}.\overline{IVP0110S} + BP0110B.\overline{BP0110PB}.\overline{BP0110L} \\
& +PP0110FSO.\overline{PP0110FM}.\overline{PP0110L}).(P0107B.\overline{P0107F}.\overline{P0107PB}.\overline{P0107L} \\
& +P0107F.\overline{P0107B}.\overline{P0107PB}.\overline{P0107L} + P0108B.\overline{P0108F}.\overline{P0108PB}.\overline{P0108L} \\
& +P0108F.\overline{P0108B}.\overline{P0108PB}.\overline{P0108L} + P0109B.\overline{P0109F}.\overline{P0109PB}.\overline{P0109L} \\
& +P0109F.\overline{P0109B}.\overline{P0109PB}.\overline{P0109L} + P0110B.\overline{P0110F}.\overline{P0110PB}.\overline{P0110L} \\
& +P0110F.\overline{P0110B}.\overline{P0110PB}.\overline{P0110L} + P0111B.\overline{P0105F}.\overline{P0111PB}.\overline{P0111L} \\
& +P0111F.\overline{P0105B}.\overline{P0111PB}.\overline{P0111L} + P0112B.\overline{P0112F}.\overline{P0112PB}.\overline{P0112L} \\
& +P0112F.\overline{P0112B}.\overline{P0112PB}.\overline{P0112L} + PP0120FSO.\overline{PP0120FM}.\overline{PP0120L} \\
& +IVP0120FC.\overline{IVP0120FO}.\overline{IVP0120B}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +IVP0120B.\overline{IVP0120FO}.\overline{IVP0120FC}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +CT0120F.\overline{CT0120T}.\overline{IVP0120FO}.\overline{IVP0120S} + BP0120B.\overline{BP0120PB}.\overline{BP0120L})
\end{aligned}$$

Number	Prime Implicants		Number	Prime Implicants
1)	$P0113B.\overline{P0113F}.\overline{P0113PB}.\overline{P0113L}$			
2)	$P0113F.\overline{P0113B}.\overline{P0113PB}.\overline{P0113L}$			
3)	$P0114B.\overline{P0114F}.\overline{P0114PB}.\overline{P0114L}$			
		OR		
1)	$P0101B.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}$		1)	$P0107B.\overline{P0107F}.\overline{P0107PB}.\overline{P0107L}$
2)	$P0101F.\overline{P0101B}.\overline{P0101PB}.\overline{P0101L}$		2)	$P0107F.\overline{P0107B}.\overline{P0107PB}.\overline{P0107L}$
3)	$PP0110FSO.\overline{PP0110FO}.\overline{PP0110FM}.\overline{PP0110L}$		3)	$PP0120FSO.\overline{PP0120FO}.\overline{PP0120FM}.\overline{PP0120L}$
4)	$P0102B.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}$		4)	$P0108B.\overline{P0108F}.\overline{P0108PB}.\overline{P0108L}$
5)	$P0102F.\overline{P0102B}.\overline{P0102PB}.\overline{P0102L}$	AND	5)	$P0108F.\overline{P0108B}.\overline{P0108PB}.\overline{P0108L}$
6)	$P0103B.\overline{P0103F}.\overline{P0103PB}.\overline{P0103L}$		6)	$P0109B.\overline{P0109F}.\overline{P0109PB}.\overline{P0109L}$
7)	$P0103F.\overline{P0103B}.\overline{P0103PB}.\overline{P0103L}$		7)	$P0109F.\overline{P0109B}.\overline{P0109PB}.\overline{P0109L}$
8)	$IVP0110B.\overline{IVP0110FC}.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110S}.\overline{IVP0110L}$		8)	$IVP0120B.\overline{IVP0120FC}.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
9)	$IVP0110FC.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110S}.\overline{IVP0110L}$		9)	$IVP0120FC.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120S}.\overline{IVP0120L}$
10)	$CT0110F.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{CT0110T}$		10)	$CT0120F.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{CT0120T}$
11)	$P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L}$		11)	$P0110B.\overline{P0110F}.\overline{P0110PB}.\overline{P0110L}$
12)	$P0104F.\overline{P0104B}.\overline{P0104PB}.\overline{P0104L}$		12)	$P0110F.\overline{P0110B}.\overline{P0110PB}.\overline{P0110L}$
13)	$P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L}$		13)	$P0111B.\overline{P0111F}.\overline{P0111PB}.\overline{P0111L}$
14)	$P0105F.\overline{P0105B}.\overline{P0105PB}.\overline{P0105L}$		14)	$P0111F.\overline{P0111B}.\overline{P0111PB}.\overline{P0111L}$
15)	$BP0110B.\overline{BP0110PB}.\overline{BP0110L}$		15)	$BP0120B.\overline{BP0120PB}.\overline{BP0120L}$
16)	$P0106B.\overline{P0106F}.\overline{P0106PB}.\overline{P0106L}$		16)	$P0112B.\overline{P0112F}.\overline{P0112PB}.\overline{P0112L}$
17)	$P0106F.\overline{P0106B}.\overline{P0106PB}.\overline{P0106L}$		17)	$P0112F.\overline{P0112B}.\overline{P0112PB}.\overline{P0112L}$

Table D.23: Prime implicants for low flow on the outflow line when flow is required in the ACTIVE operating mode

D.1.13 Partial Flow on Outflow Line when Flow is Required

$$
\begin{aligned}
\mathrm{PFOUTFLOWF} = {} & ((\overline{P0101B}\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B} \\
& .\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{PP0110FSO} \\
& +\overline{P0107B}\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B} \\
& +.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120FSO}) \\
& .(P0113PB.\overline{P0113L} + P0113L.\overline{P0113PB} + P0114PB.\overline{P0114L})) \\
& +(P0101B.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L} + P0101F.\overline{P0101B}.\overline{P0101PB}.\overline{P0101L} \\
& +P0102B.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L} + P0102F.\overline{P0102B}.\overline{P0102PB}.\overline{P0102L} \\
& +P0103B.\overline{P0103F}.\overline{P0103PB}.\overline{P0103L} + P0103F.\overline{P0103B}.\overline{P0103PB}.\overline{P0103L} \\
& +P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L} + P0104F.\overline{P0104B}.\overline{P0104PB}.\overline{P0104L} \\
& +P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L} + P0105F.\overline{P0105B}.\overline{P0105PB}.\overline{P0105L} \\
& +P0106B.\overline{P0106F}.\overline{P0106PB}.\overline{P0106L} + P0106F.\overline{P0106B}.\overline{P0106PB}.\overline{P0106L} \\
& +IVP0110FC.\overline{IVP0110FO}.\overline{IVP0110B}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +IVP0110B.\overline{IVP0110FO}.\overline{IVP0110FC}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +CT0110F.\overline{CT0110T}.\overline{IVP0110FO}.\overline{IVP0110S} + BP0110B.\overline{BP0110PB}.\overline{BP0110L} \\
& +PP0110FSO.\overline{PP0110FM}.\overline{PP0110L}) \\
& (\overline{P0107B}\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B} \\
& +.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120FSO}) \\
& .(P0107PB.\overline{P0107L} + P0107L.\overline{P0107PB} + P0108PB.\overline{P0108L} + P0108L.\overline{P0108PB} \\
& +P0109PB.\overline{P0109L} + P0109L.\overline{P0109PB} + P0110PB.\overline{P0110L} + P0110L.\overline{P0110PB} \\
& +P0111PB.\overline{P0111L} + P0111L.\overline{P0111PB}P0112PB.\overline{P0112L} + P0112L.\overline{P0112PB} \\
& +IVP0120PB.\overline{IVP0120FO}.\overline{IVP0120S}.\overline{IVP0120L} + IVP0120S.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +IVP0120L.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120S} + BP0120PB.\overline{BP0120L} + BP0120L.\overline{BP0120PB} \\
& +PP0120L.\overline{PP0120FM} + PP0120FM.\overline{PP0120L}.\overline{PP0120FO}) \\
& .(P0107B.\overline{P0107F}.\overline{P0107PB}.\overline{P0107L} + P0107F.\overline{P0107B}.\overline{P0107PB}.\overline{P0107L} \\
& +P0108B.\overline{P0108F}.\overline{P0108PB}.\overline{P0108L} + P0108F.\overline{P0108B}.\overline{P0108PB}.\overline{P0108L} \\
& +P0109B.\overline{P0109F}.\overline{P0109PB}.\overline{P0109L} + P0109F.\overline{P0109B}.\overline{P0109PB}.\overline{P0109L} \\
& +P0110B.\overline{P0110F}.\overline{P0110PB}.\overline{P0110L} + P0110F.\overline{P0110B}.\overline{P0110PB}.\overline{P0104L} \\
& +P0111B.\overline{P0111F}.\overline{P0111PB}.\overline{P0105L} + P0105F.\overline{P0111B}.\overline{P0111PB}.\overline{P0105L} \\
& +P0106B.\overline{P0112F}.\overline{P0112PB}.\overline{P0106L} + P0106F.\overline{P0112B}.\overline{P0112PB}.\overline{P0106L} \\
& +IVP0120FC.\overline{IVP0120FO}.\overline{IVP0120B}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +IVP0120B.\overline{IVP0120FO}.\overline{IVP0120FC}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L} \\
& +CT0120F.\overline{CT0120T}.\overline{IVP0120FO}.\overline{IVP0120S} + BP0120B.\overline{BP0110PB}.\overline{BP0110L} \\
& +PP0120FSO.\overline{PP0120FM}.\overline{PP0120L}) \\
& .(\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B} \\
& .\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{PP0110FSO}) \\
& .(P0101PB.\overline{P0101L} + P0101L.\overline{P0101PB} + P0102PB.\overline{P0102L} + P0102L.\overline{P0102PB} \\
& +P0103PB.\overline{P0103L} + P0103L.\overline{P0103PB} + P0104PB.\overline{P0104L} + P0104L.\overline{P0104PB} \\
& +P0105PB.\overline{P0105L} + P0105L.\overline{P0105PB}P0106PB.\overline{P0106L} + P0106L.\overline{P0106PB} \\
& +IVP0110PB.\overline{IVP0110FO}.\overline{IVP0110S}.\overline{IVP0110L} + IVP0110S.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110L} \\
& +IVP0110L.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110S} + BP0110PB.\overline{BP0110L} + BP0110L.\overline{BP0110PB} \\
& +PP0110L.\overline{PP0110FO}.\overline{PP0110FM} + PP0110FM.\overline{PP0110L}.\overline{PP0110FO}))
\end{aligned}
$$

Number	Prime Implicants			
1)	P0113PB.P0113B.P0113F.P0113L			
2)	P0113L.P0113B.P0113F.P0113PB			
3)	P0114PB.P0114B.P0114F.P0114L			
		AND		
	P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104FP0105B.P0105FP0106B.P0106F.P0113B.P0113FP0114B .BP0110B.IVP0110FC.IVP0110B.CT0110F.PP0110FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111FP0112B.P0112F.BP0120B.IVP0120FC.IVP0120B.CT0120F.PP0120FSO			
		OR		
1)	P0101B.P0101F.P0101PB.P0101L	AND	1)	P0107PB.P0107B.P0107F.P0107L
2)	P0101F.P0101B.P0101PB.P0101L		2)	P0107L.P0107B.P0107F.P0107PB
3)	PP0110FSO.PP0110FO.PP0110FM .PP0110L		3)	PP0120FM.PP0120FO.PP0120FSO .PP0120L
4)	P0102B.P0102F.P0102PB.P0102L		4)	P0108PB.P0108B.P0108F.P0108L
5)	P0102F.P0102B.P0102PB.P0102L		5)	P0108L.P0108B.P0108F.P0108PB
6)	P0103B.P0103F.P0103PB.P0103L		6)	P0109PB.P0109B.P0109F.P0109L
7)	P0103F.P0103B.P0103PB.P0103L		7)	P0109L.P0109B.P0109F.P0109PB
8)	IVP0110B.IVP0110FC.IVP0110FO.IVP0110PB .IVP0110S.IVP0110L		8)	IVP0120PB.IVP0120FC.IVP0120FO .IVP0120B.IVP0120S.IVP0120L
9)	IVP0110FC.IVP0110B.IVP0110FO.IVP0110PB .IVP0110S.IVP0110L		9)	IVP0120S.IVP0120B.IVP0120FO .IVP0120PB.IVP0120FC.IVP0120L
10)	CT0110F.IVP0110FO.IVP0110S.CT0110T		10)	IVP0120L.IVP0120FO .IVP0120S.IVP0120FC.IVP0120B.IVP0120PB
11)	P0104B.P0104F.P0104PB.P0104L		11)	P0110PB.P0110B.P0110F.P0110L
12)	P0104F.P0104B.P0104PB.P0104L		12)	P0110L.P0110B.P0110F.P0110PB
13)	P0105B.P0105F.P0105PB.P0105L		13)	P0111PB.P0111B.P0111F.P0111L
14)	P0105F.P0105B.P0105PB.P0105L		14)	P0111L.P0111B.P0111F.P0111PB
15)	BP0110B.BP0110PB.BP0110L		15)	BP0120PB.BP0120B.BP0120L
16)	P0106B.P0106F.P0106PB.P0106L		16)	P0112PB.P0112B.P0112F.P0112L
17)	P0106F.P0106B.P0106PB.P0106L		17)	P0112L.P0112B.P0112F.P0112PB
			18)	PP0120L.PP0120FO.PP0120FSO .PP0120FM
			19)	BP0120L.BP0120B.BP0120L
		AND		
	.P0113B.P0113F.P0114B.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111F.P0112B.P0112F .BP0120B.IVP0120FC.IVP0120B.CT0120F.PP0120FSO			
		OR		
1)	P0107B.P0107F.P0107PB.P0107L	AND	1)	P0101PB.P0101B.P0101F.P0101L
2)	P0107F.P0107B.P0107PB.P0107L		2)	P0101L.P0101B.P0101F.P0101PB
3)	PP0120FSO.PP0120FO.PP0120FM .PP0120L		3)	PP0110FM.PP0110FO.PP0110FSO .PP0110L
4)	P0108B.P0108F.P0108PB.P0108L		4)	P0102PB.P0102B.P0102F.P0102L
5)	P0108F.P0108B.P0108PB.P0108L		5)	P0102L.P0102B.P0102F.P0102PB
6)	P0109B.P0109F.P0109PB.P0109L		6)	P0103PB.P0103B.P0103F.P0103L
7)	P0109F.P0109B.P0109PB.P0109L		7)	P0103L.P0103B.P0103F.P0103PB
8)	IVP0120B.IVP0120FC.IVP0120FO.IVP0120PB .IVP0120S.IVP0120L		8)	IVP0110PB.IVP0110FC.IVP0110FO .IVP0110B.IVP0110S.IVP0110L
9)	IVP0120FC.IVP0120B.IVP0120FO.IVP0120PB .IVP0120S.IVP0120L		9)	IVP0110S.IVP0110B.IVP0110FO .IVP0110PB.IVP0110FC.IVP0110L
10)	CT0120F.IVP0120FO.IVP0120S.CT0120T		10)	IVP0110L.IVP0110FO .IVP0110S.IVP0110FC.IVP0110B.IVP0110PB
11)	P0110B.P0110F.P0110PB.P0110L		11)	P0104PB.P0104B.P0104F.P0104L
12)	P0110F.P0110B.P0110PB.P0110L		12)	P0104L.P0104B.P0104F.P0104PB
13)	P0111B.P0111F.P0111PB.P0111L		13)	P0105PB.P0105B.P0105F.P0105L
14)	P0111F.P0111B.P0111PB.P0111L		14)	P0105L.P0105B.P0105F.P0105PB
15)	BP0120B.BP0120PB.BP0120L		15)	BP0110PB.BP0110B.BP0110L
16)	P0112B.P0112F.P0112PB.P0112L		16)	P0106PB.P0106B.P0106F.P0106L
17)	P0112F.P0112B.P0112PB.P0112L		17)	P0106L.P0106B.P0106F.P0106PB
			18)	PP0110L.PP0110FO.PP0110FSO .PP0110FM
			19)	BP0110L.BP0110B.BP0110L
		AND		
	.P0113B.P0113F.P0114B.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0105F.P0106B.P0106F .BP0110B.IVP0110FC.IVP0110B.CT0110F.PP0110FSO			

Table D.24: Prime implicants for partial flow on the outflow line when flow is required in the ACTIVE operating mode

D.1.14 Partial Flow on Outflow Line when Low Flow is required

$$
\begin{aligned}
\mathrm{PFOUTLF} = \; & \mathrm{\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}} \\
& \mathrm{.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{PP0110FSO}} \\
& \mathrm{.((IVP0110S.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110L} + IVP0110FO.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}} \\
& \mathrm{.(P0113PB.\overline{P0113L} + P0113L.\overline{P0113PB} + P0114PB.\overline{P0114L} + P0101PB.\overline{P0101L} + P0101L.\overline{P0101PB}} \\
& \mathrm{+P0102PB.\overline{P0102L} + P0102L.\overline{P0102PB} + P0103PB.\overline{P0103L} + P0103L.\overline{P0103PB} + P0104PB.\overline{P0104L}} \\
& \mathrm{+P0104L.\overline{P0104PB} + P0105PB.\overline{P0105L} + P0105L.\overline{P0105PB} + P0106PB.\overline{P0106L}} \\
& \mathrm{+P0106L.\overline{P0106PB} + BP0110PB.\overline{BP0110L} + BP0110L.\overline{BP0110PB})).(ACTIVE.\overline{DORMANT}} \\
& \mathrm{+DORMANT.PP0110FO.\overline{ACTIVE}.\overline{PP0110FM}.\overline{PP0110L}))} \\
& \mathrm{+\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B}.\overline{P0112F}} \\
& \mathrm{.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120FSO}} \\
& \mathrm{.((IVP0120S.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L} + IVP0120FO.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}} \\
& \mathrm{.(P0113PB.\overline{P0113L} + P0114PB.\overline{P0114L} + P0107PB.\overline{P0107L} + P0108PB.\overline{P0108L} + P0109PB.\overline{P0109L}} \\
& \mathrm{+P0110PB.\overline{P0110L} + P0111PB.\overline{P0111L} + P0112PB.\overline{P0112L} + BP0120PB.\overline{BP0120L})).(ACTIVE.\overline{DORMANT}} \\
& \mathrm{+DORMANT.PP0120FO.\overline{ACTIVE}.\overline{PP0120FM}.\overline{PP0120L}))}
\end{aligned}
$$

Number	Prime Implicants
1)	$\mathrm{P0113PB.IVP0110FO.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}..\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
2)	$\mathrm{P0113L.IVP0110FO.\overline{P0113B}.\overline{P0113F}.\overline{P0113PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
3)	$\mathrm{P0114PB.IVP0110FO.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
4)	$\mathrm{P0101PB.IVP0110FO.\overline{P0101B}.\overline{P0101F}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
5)	$\mathrm{P0101L.IVP0110FO.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
6)	$\mathrm{P0102PB.IVP0110FO.\overline{P0102B}.\overline{P0102F}.\overline{P0102L}.\overline{P0101B}.\overline{P0101F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
7)	$\mathrm{P0102L.IVP0110FO.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
8)	$\mathrm{P0103PB.IVP0110FO.\overline{P0103B}.\overline{P0103F}.\overline{P0103L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
9)	$\mathrm{P0103L.IVP0110FO.\overline{P0103B}.\overline{P0103F}.\overline{P0103PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
10)	$\mathrm{P0104PB.IVP0110FO.\overline{P0104B}.\overline{P0104F}.\overline{P0104L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
11)	$\mathrm{P0104L.IVP0110FO.\overline{P0104B}.\overline{P0104F}.\overline{P0104PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
12)	$\mathrm{P0105PB.IVP0110FO.\overline{P0105B}.\overline{P0105F}.\overline{P0105L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
13)	$\mathrm{P0105L.IVP0110FO.\overline{P0105B}.\overline{P0105F}.\overline{P0105PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
14)	$\mathrm{P0106PB.IVP0110FO.\overline{P0106B}.\overline{P0106F}.\overline{P0106L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
15)	$\mathrm{P0106L.IVP0110FO.\overline{P0106B}.\overline{P0106F}.\overline{P0106PB}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{PP0110FSO}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
16)	$\mathrm{IVP0110S.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110PB}.\overline{IVP0110L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{PP0110FSO}.\overline{CT0110F}}$
17)	$\mathrm{BP0110PB.IVP0110FO.\overline{BP0110B}.\overline{BP0110L}.\overline{PP0110FSO}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
18)	$\mathrm{BP0110L.IVP0110FO.\overline{BP0110B}.\overline{BP0110PB}.\overline{PP0110FSO}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
19)	$\mathrm{PP0110FM.IVP0110FO.\overline{PP0110FO}.\overline{PP0110FSO}.\overline{PP0110L}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$
20)	$\mathrm{PP0110L.IVP0110FO.\overline{PP0110FO}.\overline{PP0110FM}.\overline{PP0110FSO}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0103B}.\overline{P0103F}.\overline{P0104B}.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0110B}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{CT0110F}.\overline{IVP0110S}.\overline{IVP0110PB}.\overline{IVP0110L}}$

Table D.25: Prime implicants for partial flow on the outflow line when low flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
21)	P0113PB.IVP0120FO.P0113B.P0113F.P0113L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B .P0111F.P0112B.P0112F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
22)	P0113L.IVP0120FO.P0113B.P0113F.P0113PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B .P0111F.P0112B.P0112F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
23)	P0114PB.IVP0120FO.P0114B.P0114F.P0114L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B .P0111F.P0112B.P0112F.P0113B.P0113F.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB.IVP0120L
24)	P0107PB.IVP0120FO.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
25)	P0107L.IVP0120FO.P0107B.P0107F.P0107PB.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
26)	P0108PB.IVP0120FO.P0108B.P0108F.P0108L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
27)	P0108L.IVP0120FO.P0108B.P0108F.P0108PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
28)	P0109PB.IVP0120FO.P0109B.P0109F.P0109L.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
29)	P0109L.IVP0120FO.P0109B.P0109F.P0109PB.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
30)	P0110PB.IVP0120FO.P0110B.P0110F.P0110L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
31)	P0110L.IVP0120FO.P0110B.P0110F.P0110PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
32)	P0111PB.IVP0120FO.P0111B.P0111F.P0111L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
33)	P0111L.IVP0120FO.P0111B.P0111F.P0111PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0112B .P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
34)	P0112PB.IVP0120FO.P0112B.P0112F.P0112L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B .P0111F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
35)	P0112L.IVP0120FO.P0112B.P0112F.P0112PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B .P0111F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB.IVP0120L
36)	IVP0120S.IVP0120FC.IVP0120B.IVP0120FO.IVP0120PB.IVP0120L.P0107B.P0107F.P0108B.P0108F.P0109B .P0109F.P0110B.P0110F.P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.PP0120FSO.CT0120F
37)	BP0120PB.IVP0120FO.BP0120B.BP0120L.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.P0114B.IVP0120FC.IVP0120B.CT0120F.IVP0120S.IVP0120PB.IVP0120L
38)	BP0120L.IVP0120FO.BP0120B.BP0120PB.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.P0114B.IVP0120FC.IVP0120B.CT0120F
39)	PP0120FM.IVP0120FO.PP0120FO.PP0120FSO.PP0120L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.CT0120F.IVP0120S.IVP0120PB.IVP0120L
40)	PP0120L.IVP0120FO.PP0120FO.PP0120FM.PP0120FSO.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.CT0120F.IVP0120S.IVP0120PB.IVP0120L

Table D.26: Prime implicants for partial flow on the outflow line when low flow is required in the ACTIVE operating mode - Table 2

Number	Prime Implicants
1)	PP0110FO.P0113PB.IVP0110FO.P0113B.P0113F.P0113L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0105F.P0106B.P0106F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
2)	PP0110FO.P0113L.IVP0110FO.P0113B.P0113F.P0113PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0105F.P0106B.P0106F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
3)	PP0110FO.P0114PB.IVP0110FO.P0114B.P0114F.P0114L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0105F.P0106B.P0106F.P0113B.P0113F.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
4)	PP0110FO.P0101PB.IVP0110FO.P0101B.P0101F.P0101L.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
5)	PP0110FO.P0101L.IVP0110FO.P0101B.P0101F.P0101PB.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
6)	PP0110FO.P0102PB.IVP0110FO.P0102B.P0102F.P0102L.P0101B.P0101F.P0103B.P0103F.P0104B.P0104F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L

Table D.27: Prime implicants for partial flow on the outflow line in the DORMANT operating mode - Table 1

Number	Prime Implicants
7)	PP0110FO.P0102L.IVP0110FO.P0102B.P0102F.P0102PB.P0101B.P0101F.P0103B.P0103F.P0104B.P0104F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
8)	PP0110FO.P0103PB.IVP0110FO.P0103B.P0103F.P0103L.P0101B.P0101F.P0102B.P0102F.P0104B.P0104F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
	.P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
10)	PP0110FO.P0104PB.IVP0110FO.P0104B.P0104F.P0104L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
11)	PP0110FO.P0104L.IVP0110FO.P0104B.P0104F.P0104PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0105B.P0105F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
12)	PP0110FO.P0105PB.IVP0110FO.P0105B.P0105F.P0105L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0106B .P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
13)	PP0110FO.P0105L.IVP0110FO.P0105B.P0105F.P0105PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
14)	PP0110FO.P0106PB.IVP0110FO.P0106B.P0106F.P0106L.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0105F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
15)	PP0110FO.P0106L.IVP0110FO.P0106B.P0106F.P0106PB.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B.P0104F .P0105B.P0105F.P0113B.P0113F.P0114B.BP0110B.IVP0110FC.IVP0110B.PP0110FSO.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
16)	PP0110FO.IVP0110S.IVP0110FC.IVP0110B.IVP0110FO.IVP0110PB.IVP0110L.P0101B.P0101F.P0102B.P0102F.P0103B .P0103F.P0104B.P0104F.P0105B.P0105F.P0106B.P0106F.P0113B.P0113F.P0114B.BP0110B.PP0110FSO.CT0110F .PP0110FM.PP0110L
17)	PP0110FO.BP0110PB.IVP0110FO.BP0110B.BP0110L.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0105F.P0106B.P0106F.P0113B.P0113F.P0114B.IVP0110FC.IVP0110B.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
18)	PP0110FO.BP0110L.IVP0110FO.BP0110B.BP0110PB.PP0110FSO.P0101B.P0101F.P0102B.P0102F.P0103B.P0103F.P0104B .P0104F.P0105B.P0105F.P0106B.P0106F.P0113B.P0113F.P0114B.IVP0110FC.IVP0110B.CT0110F.IVP0110S.IVP0110PB .IVP0110L.PP0110FM.PP0110L
19)	PP0120FO.P0113PB.IVP0120FO.P0113B.P0113F.P0113L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
20)	PP0120FO.P0113L.IVP0120FO.P0113B.P0113F.P0113PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
21)	PP0120FO.P0114PB.IVP0120FO.P0114B.P0114F.P0114L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F .P0111B.P0111F.P0112B.P0112F.P0113B.P0113F.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
22)	PP0120FO.P0107PB.IVP0120FO.P0107B.P0107F.P0107L.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
23)	PP0120FO.P0107L.IVP0120FO.P0107B.P0107F.P0107PB.P0108B.P0108F.P0109B.P0109F.P0110B.P0110F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
24)	PP0120FO.P0108PB.IVP0120FO.P0108B.P0108F.P0108L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
25)	PP0120FO.P0108L.IVP0120FO.P0108B.P0108F.P0108PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
26)	PP0120FO.P0109PB.IVP0120FO.P0109B.P0109F.P0109L.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
27)	PP0120FO.P0109L.IVP0120FO.P0109B.P0109F.P0109PB.P0107B.P0107F.P0108B.P0108F.P0110B.P0110F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
28)	PP0120FO.P0110PB.IVP0120FO.P0110B.P0110F.P0110L.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L
29)	PP0120FO.P0110L.IVP0120FO.P0110B.P0110F.P0110PB.P0107B.P0107F.P0108B.P0108F.P0109B.P0109F.P0111B.P0111F .P0112B.P0112F.P0113B.P0113F.P0114B.BP0120B.IVP0120FC.IVP0120B.PP0120FSO.CT0120F.IVP0120S.IVP0120PB .IVP0120L.PP0120FM.PP0120L

Table D.28: Prime implicants for partial flow on the outflow line in the DORMANT operating mode - Table 2

Number	Prime Implicants
30)	$PP0120FO.P0111PB.IVP0120FO.\overline{P0111B}.\overline{P0111F}.\overline{P0111L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0112B}.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{PP0120FM}.\overline{PP0120L}$
31)	$PP0120FO.P0111L.IVP0120FO.\overline{P0111B}.\overline{P0111F}.\overline{P0111PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0112B}.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{PP0120FM}.\overline{PP0120L}$
32)	$PP0120FO.P0112PB.IVP0120FO.\overline{P0112B}.\overline{P0112F}.\overline{P0112L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{PP0120FM}.\overline{PP0120L}$
33)	$PP0120FO.P0112L.IVP0120FO.\overline{P0112B}.\overline{P0112F}.\overline{P0112PB}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{PP0120FM}.\overline{PP0120L}$
34)	$PP0120FO.IVP0120S.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{IVP0120FO}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B}.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{BP0120B}.\overline{PP0120FSO}.\overline{CT0120F}.\overline{PP0120FM}.\overline{PP0120L}$
35)	$PP0120FO.BP0120PB.IVP0120FO.\overline{BP0120B}.\overline{BP0120L}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B}.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{IVP0120S}.\overline{IVP0120PB}.\overline{IVP0120L}.\overline{PP0120FM}.\overline{PP0120L}$
36)	$PP0120FO.BP0120L.IVP0120FO.\overline{BP0120B}.\overline{BP0120PB}.\overline{PP0120FSO}.\overline{P0107B}.\overline{P0107F}.\overline{P0108B}.\overline{P0108F}.\overline{P0109B}.\overline{P0109F}.\overline{P0110B}.\overline{P0110F}.\overline{P0111B}.\overline{P0111F}.\overline{P0112B}.\overline{P0112F}.\overline{P0113B}.\overline{P0113F}.\overline{P0114B}.\overline{IVP0120FC}.\overline{IVP0120B}.\overline{CT0120F}.\overline{PP0120FM}.\overline{PP0120L}$

Table D.29: Prime implicants for partial flow on the outflow line in the DORMANT operating mode - Table 3

D.1.15 High Flow at PSV0110

$$
\begin{aligned}
HFPSV0110 = \; & (P0103B.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}\overline{P0115B}.\overline{P0115F} \\
& .\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117F}.\overline{PP0110FSO}.\overline{PP0110FM} \\
& .\overline{PP0110L}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{P0103F}.\overline{P0103L}.\overline{P0103PB} \\
& +(.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}.\overline{P0115B}.\overline{P0115F} \\
& .\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117F}.\overline{PP0110FSO}.\overline{PP0110FM} \\
& .\overline{PP0110L}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{P0103F}.\overline{P0103L}.\overline{IVP0110L} \\
& .\overline{IVP0110S}).(P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L} + P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L}.\overline{P0104L} \\
& +P0106B.\overline{P0106F}.\overline{P0106PB}.\overline{P0106L}.\overline{P0104L}.\overline{P0105L} + IVP0110FC.\overline{IVP0110FO}.\overline{IVP0110B}.\overline{IVP0110PB} \\
& +P0113B.\overline{P0113F}.\overline{P0113PB}.\overline{P0113L}.\overline{BP0110L}.\overline{P0104L}.\overline{P0105L}.\overline{P0106L} \\
& +P0114B.\overline{P0114F}.\overline{P0114PB}.\overline{P0114L}.\overline{BP0110L}.\overline{P0104L}.\overline{P0105L}.\overline{P0106L}.\overline{P0113L} \\
& +CT0110F.\overline{CT0110T}.\overline{IVP0110FO} + BP0110B.\overline{BP0110PB}.\overline{BP0110L}.\overline{P0104L}.\overline{P0105L}).(ACTIVE.\overline{DORMANT})) \\
& +DORMANT.PP0110FO.\overline{ACTIVE}.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L} \\
& .\overline{P0115B}.\overline{P0115F}.\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117F}.\overline{PP0110FSO}.\overline{PP0110FM} \\
& .\overline{PP0110L}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{P0103F}.\overline{P0103L}
\end{aligned}
$$

Number	Prime Implicants
1)	$P0103B.\overline{P0103F}.\overline{P0103PB}.\overline{P0103L}.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}.\overline{P0115B}.\overline{P0115F}.\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117PB}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{PP0110FSO}.\overline{PP0110FM}.\overline{PP0110L}$
2)	$P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L}.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0103F}.\overline{P0103L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}.\overline{P0115B}.\overline{P0115F}.\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117PB}.\overline{IVP0110L}.\overline{IVP0110S}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{PP0110FSO}.\overline{PP0110FM}.\overline{PP0110L}$
3)	$P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L}.\overline{P0101B}.\overline{P0101F}.\overline{P0101PB}.\overline{P0101L}.\overline{P0103F}.\overline{P0103L}.\overline{P0102B}.\overline{P0102F}.\overline{P0102PB}.\overline{P0102L}.\overline{P0115B}.\overline{P0115F}.\overline{P0115PB}.\overline{P0115L}.\overline{P0116B}.\overline{P0116F}.\overline{P0116PB}.\overline{P0116L}.\overline{P0117B}.\overline{P0117PB}.\overline{IVP0110L}.\overline{IVP0110S}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{PSV0110PB}.\overline{PSV0110S}.\overline{PSV0110L}.\overline{PP0110FSO}.\overline{PP0110FM}.\overline{PP0110L}.\overline{P0104L}$

Table D.30: Prime implicants for high flow at PSV0110 when in the ACTIVE operating mode - Table 1

Number	Prime Implicants
4)	$\mathrm{P0106B}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0106L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105L}}$
5)	$\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0120L}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105L}}.\overline{\mathrm{P0106L}}.\overline{\mathrm{BP0110L}}$
6)	$\mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105L}}.\overline{\mathrm{P0106L}}.\overline{\mathrm{P0113L}}.\overline{\mathrm{BP0110L}}$
7)	$\mathrm{IVP0110FC}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0117L}}$
8)	$\mathrm{IVP0110B}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}$
9)	$\mathrm{CT0110F}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}$
10)	$\mathrm{BP0110B}.\overline{\mathrm{BP0110L}}.\overline{\mathrm{BP0110PB}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0105L}}$

Table D.31: Prime implicants for high flow at PSV0110 when in the ACTIVE operating mode - Table 2

Number	Prime Implicants
1)	$\mathrm{PP0110FO}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117F}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}$

Table D.32: Prime implicants for high flow at PSV0110 when in the DORMANT operating mode

D.1.16 High Flow at PSV0120

$$
\begin{aligned}
\mathrm{HFPSV0120} = {} & (\mathrm{P0109B}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0108L}}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}} \\
& .\overline{\mathrm{P0118PB}}.\overline{\mathrm{P0118L}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119PB}}.\overline{\mathrm{P0119L}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0120F}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}} \\
& .\overline{\mathrm{PP0120L}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109L}}.\overline{\mathrm{P0109PB}} \\
& +(.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}}.\overline{\mathrm{P0108L}}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}} \\
& .\overline{\mathrm{P0118PB}}.\overline{\mathrm{P0118L}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119PB}}.\overline{\mathrm{P0119L}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0120F}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}} \\
& .\overline{\mathrm{PP0120L}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109L}}.\overline{\mathrm{IVP0120L}} \\
& .\overline{\mathrm{IVP0120S}}).(\mathrm{P0110B}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}} + \mathrm{P0111B}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111PB}}.\overline{\mathrm{P0111L}}.\overline{\mathrm{P0110L}} \\
& +\mathrm{P0112B}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0112L}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0111L}} + \mathrm{IVP0120FC}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120PB}} \\
& +\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}.\overline{\mathrm{BP0120L}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0111L}}.\overline{\mathrm{P0112L}} \\
& +\mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}}.\overline{\mathrm{BP0120L}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0111L}}.\overline{\mathrm{P0112L}}.\overline{\mathrm{P0113L}} \\
& +\mathrm{CT0120F}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120FO}} + \mathrm{BP0120B}.\overline{\mathrm{BP0120PB}}.\overline{\mathrm{BP0120L}}.\overline{\mathrm{P0110L}}.\overline{\mathrm{P0111L}}).(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}})) \\
& +\mathrm{DORMANT}.\mathrm{PP0120FO}.\overline{\mathrm{ACTIVE}}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0108L}} \\
& .\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0118PB}}.\overline{\mathrm{P0118L}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119PB}}.\overline{\mathrm{P0119L}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0120F}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}} \\
& .\overline{\mathrm{PP0120L}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109L}}
\end{aligned}
$$

Number	Prime Implicants
1)	P0109B.P0109F.P0109PB.P0109L.P0107B.P0107F.P0107PB.P0107L.P0108B.P0108F.P0108PB.P0108L.P0118B .P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.PSV0120ISC.PSV0120B.PSV0120PB .PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L
2)	P0110B.P0110F.P0110PB.P0110L.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L
3)	P0111B.P0111F.P0111PB.P0111L.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L.P0110L
4)	P0112B.P0112F.P0112PB.P0112L.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L.P0110L.P0111L
5)	P0113B.P0113F.P0113PB.P0113L.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L.P0110L.P0111L.P0112L .BP0110L
6)	P0114B.P0114F.P0114PB.P0114L.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L.P0110L.P0111L.P0112L .P0113L.BP0120L
7)	IVP0120FC.IVP0120FO.IVP0120B.IVP0120S.IVP0120PB.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B .P0108F.P0108PB.P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L
8)	IVP0120B.IVP0120FC.IVP0120FO.IVP0120S.IVP0120PB.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B .P0108F.P0108PB.P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L
9)	CT0120F.IVP0120FO.IVP0120S.CT0120T.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L
10)	BP0120B.BP0120L.BP0120PB.P0107B.P0107F.P0107PB.P0107L.P0109F.P0109L.P0108B.P0108F.P0108PB .P0108L.P0118B.P0118F.P0118PB.P0118L.P0119B.P0119F.P0119PB.P0119L.P0120B.P0120PB.IVP0120L.IVP0120S .PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L.PP0120FSO.PP0120FM.PP0120L.P0110L.P0111L

Table D.33: Prime implicants for high flow at PSV0120 when in the ACTIVE operating mode

Number	Prime Implicants
1)	PP0120FO.P0107B.P0107F.P0107PB.P0107L.P0108B.P0108F.P0108PB.P0108L.P0118B.P0118F.P0118PB .P0118L.P0119B.P0119F .P0119PB.P0119L.P0120B.P0120F.PP0120FSO.PP0120FM.PP0120L.PSV0120ISC.PSV0120B.PSV0120PB.PSV0120S.PSV0120L .P0109F.P0109L

Table D.34: Prime implicants for high flow at PSV0120 when in the DORMANT operating mode

D.1.17 Low Flow at PSV0110

$$
\begin{aligned}
\mathrm{LFPSV0110} = {} & \mathrm{P0101B}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}} + \mathrm{P0101F}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}} + \mathrm{P0102B}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}} \\
& + \mathrm{P0102F}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102L}} + \mathrm{P0103F}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}} + \mathrm{P0115B}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}} \\
& + \mathrm{P0115F}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}} + \mathrm{P0116B}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}} + \mathrm{P0116F}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}} \\
& + \mathrm{P0117B}.\overline{\mathrm{P0117F}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{P0117L}} + \mathrm{PP0110FSO}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}} \\
& + \mathrm{PSV0110ISC}.\overline{\mathrm{PSV0110ISO}}.\mathrm{PSV0110S}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110L}} \\
& + \mathrm{PSV0110B}.\overline{\mathrm{PSV0110ISO}}.\mathrm{PSV0110S}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110L}} \\
& + \mathrm{IVP0110FO}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\mathrm{IVP0110L}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}} \\
& .\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{BP0110B}} \\
& + \mathrm{CT0110T}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\mathrm{IVP0110S}.\overline{\mathrm{IVP0110PB}}.\mathrm{IVP0110L}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}} \\
& .\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{CT0110F}}
\end{aligned}
$$

Number	Prime Implicants
1)	PP0110FSO.$\overline{\text{PP0110FO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110L}}$
2)	P0115B.$\overline{\text{P0115F}}$.$\overline{\text{P0115PB}}$.$\overline{\text{P0115L}}$
3)	P0115F.$\overline{\text{P0115B}}$.$\overline{\text{P0115PB}}$.$\overline{\text{P0115L}}$
4)	P0116B.$\overline{\text{P0116F}}$.$\overline{\text{P0116PB}}$.$\overline{\text{P0116L}}$
5)	P0116F.$\overline{\text{P0116B}}$.$\overline{\text{P0116PB}}$.$\overline{\text{P0116L}}$
6)	P0117B.$\overline{\text{P0117F}}$.$\overline{\text{P0117PB}}$.$\overline{\text{P0117L}}$
7)	P0101B.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$
8)	P0101F.$\overline{\text{P0101B}}$.$\overline{\text{P0101PB}}$.$\overline{\text{P0101L}}$
9)	P0102B.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$
10)	P0102F.$\overline{\text{P0102B}}$.$\overline{\text{P0102PB}}$.$\overline{\text{P0102L}}$
11)	P0103F.$\overline{\text{P0103B}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$
12)	PSV0110ISC.$\overline{\text{PSV0110ISO}}$.$\overline{\text{PSV0110S}}$.$\overline{\text{PSV0110PB}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{PSV0110L}}$
13)	PSV0110B.$\overline{\text{PSV0110ISO}}$.$\overline{\text{PSV0110S}}$.$\overline{\text{PSV0110PB}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110L}}$
14)	IVP0110FO.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110B}}$
15)	CT0110T.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110B}}$.$\overline{\text{CT0110F}}$

Table D.35: Prime implicants for low flow at PSV0110 when in the ACTIVE operating mode

D.1.18 Low Flow at PSV0120

$$
\begin{aligned}
\text{LFPSV0120} = \;& \text{P0107B}.\overline{\text{P0107F}}.\overline{\text{P0107PB}}.\overline{\text{P0107L}} + \text{P0107F}.\overline{\text{P0107B}}.\overline{\text{P0107PB}}.\overline{\text{P0107L}} + \text{P0108B}.\overline{\text{P0108F}}.\overline{\text{P0108PB}}.\overline{\text{P0108L}} \\
& + \text{P0108F}.\overline{\text{P0108B}}.\overline{\text{P0108PB}}.\overline{\text{P0108L}} + \text{P0103F}.\overline{\text{P0103B}}.\overline{\text{P0103PB}}.\overline{\text{P0103L}} + \text{P0115B}.\overline{\text{P0115F}}.\overline{\text{P0115PB}}.\overline{\text{P0115L}} \\
& + \text{P0115F}.\overline{\text{P0115B}}.\overline{\text{P0115PB}}.\overline{\text{P0115L}} + \text{P0116B}.\overline{\text{P0116F}}.\overline{\text{P0116PB}}.\overline{\text{P0116L}} + \text{P0116F}.\overline{\text{P0116B}}.\overline{\text{P0116PB}}.\overline{\text{P0116L}} \\
& + \text{P0117B}.\overline{\text{P0117F}}.\overline{\text{P0117PB}}.\overline{\text{P0117L}} + \text{PP0110FSO}.\overline{\text{PP0110FO}}.\overline{\text{PP0110FM}}.\overline{\text{PP0110L}} \\
& + \text{PSV0110ISC}.\overline{\text{PSV0110ISO}}.\overline{\text{PSV0110S}}.\overline{\text{PSV0110PB}}.\overline{\text{PSV0110B}}.\overline{\text{PSV0110L}} \\
& + \text{PSV0110B}.\overline{\text{PSV0110ISO}}.\overline{\text{PSV0110S}}.\overline{\text{PSV0110PB}}.\overline{\text{PSV0110ISC}}.\overline{\text{PSV0110L}} \\
& + \text{IVP0110FO}.\overline{\text{IVP0110FC}}.\overline{\text{IVP0110B}}.\overline{\text{IVP0110S}}.\overline{\text{IVP0110PB}}.\overline{\text{IVP0110L}}.\overline{\text{P0103B}}.\overline{\text{P0103PB}}.\overline{\text{P0104B}} \\
& .\overline{\text{P0104PB}}.\overline{\text{P0105B}}.\overline{\text{P0105PB}}.\overline{\text{P0106B}}.\overline{\text{P0106PB}}.\overline{\text{P0113B}}.\overline{\text{P0113PB}}.\overline{\text{P0114B}}.\overline{\text{P0114PB}}.\overline{\text{BP0110B}} \\
& + \text{CT0110T}.\overline{\text{IVP0110FC}}.\overline{\text{IVP0110B}}.\overline{\text{IVP0110S}}.\overline{\text{IVP0110PB}}.\overline{\text{IVP0110L}}.\overline{\text{P0103B}}.\overline{\text{P0103PB}}.\overline{\text{P0104B}} \\
& .\overline{\text{P0104PB}}.\overline{\text{P0105B}}.\overline{\text{P0105PB}}.\overline{\text{P0106B}}.\overline{\text{P0106PB}}.\overline{\text{P0113B}}.\overline{\text{P0113PB}}.\overline{\text{P0114B}}.\overline{\text{P0114PB}}.\overline{\text{BP0110B}}.\overline{\text{CT0110F}}
\end{aligned}
$$

Number	Prime Implicants
1)	PP0120FSO.$\overline{\text{PP0120FO}}$.$\overline{\text{PP0120FM}}$.$\overline{\text{PP0120L}}$
2)	P0118B.$\overline{\text{P0118F}}$.$\overline{\text{P0118PB}}$.$\overline{\text{P0118L}}$
3)	P0118F.$\overline{\text{P0118B}}$.$\overline{\text{P0118PB}}$.$\overline{\text{P0118L}}$
4)	P0119B.$\overline{\text{P0119F}}$.$\overline{\text{P0119PB}}$.$\overline{\text{P0119L}}$
5)	P0119F.$\overline{\text{P0119B}}$.$\overline{\text{P0119PB}}$.$\overline{\text{P0119L}}$
6)	P0120B.$\overline{\text{P0120F}}$.$\overline{\text{P0120PB}}$.$\overline{\text{P0120L}}$
7)	P0107B.$\overline{\text{P0107F}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$
8)	P0107F.$\overline{\text{P0107B}}$.$\overline{\text{P0107PB}}$.$\overline{\text{P0107L}}$
9)	P0108B.$\overline{\text{P0108F}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$
10)	P0108F.$\overline{\text{P0108B}}$.$\overline{\text{P0108PB}}$.$\overline{\text{P0108L}}$
11)	P0109F.$\overline{\text{P0109B}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0109L}}$
12)	PSV0120ISC.$\overline{\text{PSV0120ISO}}$.$\overline{\text{PSV0120S}}$.$\overline{\text{PSV0120PB}}$.$\overline{\text{PSV0120B}}$.$\overline{\text{PSV0120L}}$
13)	PSV0120B.$\overline{\text{PSV0120ISO}}$.$\overline{\text{PSV0120S}}$.$\overline{\text{PSV0120PB}}$.$\overline{\text{PSV0120ISC}}$.$\overline{\text{PSV0120L}}$
14)	IVP0120FO.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120B}}$
15)	CT0120T.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{P0109B}}$.$\overline{\text{P0109PB}}$.$\overline{\text{P0110B}}$.$\overline{\text{P0110PB}}$.$\overline{\text{P0111B}}$.$\overline{\text{P0111PB}}$.$\overline{\text{P0112B}}$.$\overline{\text{P0112PB}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114PB}}$.$\overline{\text{BP0120PB}}$.$\overline{\text{BP0120B}}$.$\overline{\text{CT0120F}}$

Table D.36: Prime implicants for low flow at PSV0120 when in the ACTIVE operating mode

D.1.19 Partial Flow at PSV0110 when Low Flow is Required

$\mathrm{PFPSV0110LFA} = \mathrm{\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0115B}.\overline{P0115F}.\overline{P0116B}.\overline{P0116FB}.\overline{P0117B}.\overline{P0103F}.\overline{IVP0110FO}}$
$\mathrm{.\overline{PP0110FSO}.\overline{PSV0110ISC}.\overline{PSV0110B}.\overline{CT0110T}.(P0103PB.\overline{P0103B}.\overline{P0103L}}$
$\mathrm{+P0104PB.\overline{P0104B}.\overline{P0104F}.\overline{P0104L} + P0105PB.\overline{P0104F}.\overline{P0105B}.\overline{P0105F}.\overline{P0105L}}$
$\mathrm{+P0106PB.\overline{P0104F}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{P0105L}}$
$\mathrm{+P0113PB.\overline{P0104F}.\overline{P0105F}.\overline{P0106F}.\overline{P0113B}.\overline{P0113F}.\overline{P0113L}}$
$\mathrm{+P0114PB.\overline{P0104F}.\overline{P0105F}.\overline{P0106F}.\overline{P0113F}.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}}$
$\mathrm{+IVP0110S.\overline{IVP0110PB}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110L}}$
$\mathrm{+IVP0110PB.\overline{IVP0110S}.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110L} + BP0110PB.\overline{BP0110L}.\overline{BP0110B})}$
$\mathrm{+(P0103B.\overline{P0103F}.\overline{P0103PB}.\overline{P0103L} + P0104B.\overline{P0104F}.\overline{P0104PB}.\overline{P0104L}}$
$\mathrm{+P0105B.\overline{P0105F}.\overline{P0105PB}.\overline{P0105L} + P0106B.\overline{P0106F}.\overline{P0106PB}.\overline{P0106L}}$
$\mathrm{+P0113B.\overline{P0113F}.\overline{P0113PB}.\overline{P0113L} + P0114B.\overline{P0114F}.\overline{P0114PB}.\overline{P0114L}}$
$\mathrm{+IVP0110S.\overline{IVP0110FO}.\overline{IVP0110B}.\overline{IVP0110PB}.\overline{IVP0110FC}.\overline{IVP0110L}}$
$\mathrm{+IVP0110B.\overline{IVP0110FO}.\overline{IVP0110FC}.\overline{IVP0110PB}.\overline{IVP0110S}.\overline{IVP0110L}}$
$\mathrm{+IVP0110FC.\overline{IVP0110FO}.\overline{IVP0110B}.\overline{BP0110B}.\overline{BP0110PB}.\overline{BP0110L})}$
$\mathrm{.(P0101PB.\overline{P0101B}.\overline{P0101F}.\overline{P0101L} + P0101L.\overline{P0101B}.\overline{P0101F}.\overline{P0101L}}$
$\mathrm{+P0102PB.\overline{P0102B}.\overline{P0102F}.\overline{P0102L} + P0102L.\overline{P0102B}.\overline{P0102F}.\overline{P0102L}}$
$\mathrm{+P0115PB.\overline{P0115B}.\overline{P0115F}.\overline{P0115L} + P0115L.\overline{P0115B}.\overline{P0115F}.\overline{P0115L}}$
$\mathrm{+P0116PB.\overline{P0116B}.\overline{P0116F}.\overline{P0116L} + P0116L.\overline{P0116B}.\overline{P0116F}.\overline{P0116L}}$
$\mathrm{+P0117PB.\overline{P0117B}.\overline{P0117F}.\overline{P0117L} + P0103L.\overline{P0103B}.\overline{P0103F}.\overline{P0103L}}$
$\mathrm{+PP0110FM.\overline{PP0110FSO}.\overline{PP0110L} + PP0110L.\overline{PP0110FSO}.\overline{PP0110FM}}$
$\mathrm{+(PSV0110S.\overline{PSV0110PB}.\overline{PSV0110L} + PSV0110PB.\overline{PSV0110S}.\overline{PSV0110L}}$
$\mathrm{+PSV0110L.\overline{PSV0110PB}.\overline{PSV0110S}).(\overline{PSV0110B}.\overline{PSV0110ISC}.\overline{PSV0110ISO})}$
$\mathrm{+(\overline{P0103B}.\overline{P0104B}.\overline{P0104F}.\overline{IVP0110B}.\overline{IVP0110FC}.\overline{CT0110F}).(P0104L.\overline{P0104PB}}$
$\mathrm{+P0105L.\overline{P0105B}.\overline{P0105F}.\overline{P0105PB} + P0106L.\overline{P0106B}.\overline{P0106F}.\overline{P0106PB}.\overline{P0105B}.\overline{P0105F}}$
$\mathrm{+P0113L.\overline{P0113B}.\overline{P0113F}.\overline{P0113PB}.\overline{P0105B}.\overline{P0105F}.\overline{P0106B}.\overline{P0106F}.\overline{BP0110B}}$
$\mathrm{+BP0110L.\overline{BP0110B}.\overline{BP0110PB}.\overline{P0105B}.\overline{P0105F})).(ACTIVE.\overline{DORMANT})}$

$\mathrm{LFPSV0110FD} = \mathrm{PP0110FO.\overline{PP0110FSO}.\overline{PP0110FM}.\overline{PP0110L}.(\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0115B}.\overline{P0115F}.\overline{P0116B}}$
$\mathrm{.\overline{P0116F}.\overline{P0117B}.\overline{P0103F}.\overline{PSV0110ISC}.\overline{PSV0110B}.(\overline{IVP0110FO}.\overline{CT0110T} + P0115PB.\overline{P0115L}}$
$\mathrm{+P0115L.\overline{P0115PB} + P0116PB.\overline{P0116L} + P0116L.\overline{P0116PB} + P0117PB.\overline{P0117L}}$
$\mathrm{+P0101PB.\overline{P0101L} + P0101L.\overline{P0101PB} + P0102PB.\overline{P0102L} + P0102L.\overline{P0102PB}}$
$\mathrm{+P0103PB.\overline{P0103L} + P0103L.\overline{P0103PB} + PSV0110S.\overline{PSV0110ISO}.\overline{PSV0110L}}$
$\mathrm{+PSV0110L.\overline{PSV0110ISO}.\overline{PSV0110S} + PSV0110ISO.\overline{PSV0110S}.\overline{PSV0110L}}$
$\mathrm{+IVP0110S.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110PB}.\overline{IVP0110FC}.\overline{IVP0110L})}$
$\mathrm{+(\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0115B}.\overline{P0115F}.\overline{P0116B}.\overline{P0116F}.\overline{P0117B}.\overline{P0103F}.\overline{PSV0110ISC}}$
$\mathrm{.\overline{PSV0110B}.((IVP0110FO.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110PB}.\overline{IVP0110S}.\overline{IVP0110L}}$
$\mathrm{+CT0110T.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110PB}.\overline{IVP0110S}.\overline{IVP0110L}.\overline{CT0110F})}$
$\mathrm{.(P0103PB.\overline{P0103B}.\overline{P0103F}.\overline{P0103L} + P0104PB.\overline{P0104B}.\overline{P0104F}.\overline{P0104L}}$
$\mathrm{+P0105PB.\overline{P0105B}.\overline{P0105F}.\overline{P0105L} + P0106PB.\overline{P0106B}.\overline{P0106F}.\overline{P0106L}}$
$\mathrm{+P0113PB.\overline{P0113B}.\overline{P0113F}.\overline{P0113L} + P0114PB.\overline{P0114B}.\overline{P0114F}.\overline{P0114L}}$
$\mathrm{+BP0110PB.\overline{BP0110B}.\overline{BP0110L})) + IVP0110PB.CT0110T.\overline{IVP0110FC}.\overline{IVP0110B}.\overline{IVP0110FO}.\overline{IVP0110S}}$
$\mathrm{.\overline{IVP0110L}.\overline{CT0110F}.\overline{P0101B}.\overline{P0101F}.\overline{P0102B}.\overline{P0102F}.\overline{P0115B}.\overline{P0115F}.\overline{P0116B}.\overline{P0116F}.\overline{P0117B}.\overline{P0103F}}$
$\mathrm{.\overline{PSV0110ISC}.\overline{PSV0110B}).(DORMANT.\overline{ACTIVE}))}$

Number	Prime Implicants
1)	P0103PB.$\overline{\text{P0103F}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
2)	P0104PB.$\overline{\text{P0104F}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
3)	P0105PB.$\overline{\text{P0105F}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
4)	P0106PB.$\overline{\text{P0106F}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
5)	P0113PB.$\overline{\text{P0113F}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
6)	P0114PB.$\overline{\text{P0114F}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
7)	IVP0110S.$\overline{\text{IVP0110FO}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
8)	IVP0110PB.$\overline{\text{IVP0110FO}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$
9)	BP0110PB.$\overline{\text{BP0110L}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{IVP0110FO}}$$\overline{\text{PP0110FSO}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{CT0110T}}$

Table D.37: Prime implicants for partial flow at PSV0110 when flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants			
1)	P0103B.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$.$\overline{\text{P0103L}}$		1)	P0101PB.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101L}}$
2)	P0104B.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0104L}}$		2)	P0101L.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0101PB}}$
3)	P0105B.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0105L}}$		3)	P0102PB.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102L}}$
4)	P0106B.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0106L}}$		4)	P0102L.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0102PB}}$
5)	P0113B.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0113L}}$		5)	P0115PB.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0115L}}$
6)	P0114B.$\overline{\text{P0114F}}$.$\overline{\text{P0114PB}}$.$\overline{\text{P0114L}}$		2)	P0115L.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0115PB}}$
7)	IVP0110FC.$\overline{\text{IVP0110FO}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$		7)	P0116PB.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0116L}}$
			8)	P0116L.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0116PB}}$
8)	IVP0110B.$\overline{\text{IVP0110FO}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$		9)	P0117PB.$\overline{\text{P0117B}}$.$\overline{\text{P0117F}}$.$\overline{\text{P0117L}}$
		AND	10)	PSV0110S.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110ISO}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{PSV0110PB}}$.$\overline{\text{PSV0110L}}$
9)	BP0110B.$\overline{\text{BP0110PB}}$.$\overline{\text{BP0110L}}$		11)	PSV0110PB.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110ISO}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{PSV0110S}}$.$\overline{\text{PSV0110L}}$
			12)	PSV0110L.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110ISO}}$.$\overline{\text{PSV0110B}}$.$\overline{\text{PSV0110PB}}$.$\overline{\text{PSV0110S}}$
			13)	PP0110FM.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FO}}$.$\overline{\text{PP0110L}}$
			14)	PP0110L.$\overline{\text{PP0110FSO}}$.$\overline{\text{PP0110FO}}$.$\overline{\text{PP0110FM}}$
			15)	P0103L.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103PB}}$
			16)	P0104L.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104PB}}$.$\overline{\text{P0103B}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{CT0110F}}$
			17)	P0105L.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105PB}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{CT0110F}}$
			18)	P0106L.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106PB}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{CT0110F}}$.$\overline{\text{BP0110B}}$
			19)	P0113L.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113PB}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{CT0110F}}$.$\overline{\text{BP0110B}}$
			20)	BP0110L.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110PB}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{CT0110F}}$

Table D.38: Prime implicants for partial flow at IVP0110 when flow is required in the ACTIVE operating mode - Table 2

Number	Prime Implicants
1)	P0115PB.PP0110FO.P0115F.P0115B.P0115L.P0101B.P0101F.P0102B.P0102F .P0103F.P0116B.P0116F.P0117B.IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
2)	P0115L.PP0110FO.P0115B.P0115PB.P0115F.P0101B.P0101F.P0102B.P0102F .P0103F.P0116B.P0116F.P0117B.IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
3)	P0116PB.PP0110FO.P0116F.P0116B.P0116L.P0101B.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0117B .IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
4)	P0116L.PP0110FO.P0116B.P0116PB.P0116F.P0101B.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0117B .IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
5)	P0117PB.PP0110FO.P0117F.P0117B.P0117L.P0101B.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F .IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
6)	P0101PB.PP0110FO.P0101F.P0101B.P0101L.P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO .PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
7)	P0101L.PP0110FO.P0101B.P0101PB.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO .PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
8)	P0102PB.PP0110FO.P0102F.P0102B.P0102L.P0101B.P0101F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO .PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
9)	P0102L.PP0110FO.P0102B.P0102PB.P0102F.P0101B.P0101F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO .PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
10)	P0103L.PP0110FO.P0103B.P0103PB.P0103F.P0101B.P0101F.P0102B.P0102F.P0115B.P0115F.P0116B.P0116F.P0117B .IVP0110FO.PP0110FSO.PSV0110ISC.PSV0110B.CT0110T.PP0110FSO.PP0110FM.PP0110L
11)	PSV0110S.PP0110FO.PSV0110ISO.PSV0110ISC.PSV0110PB.PSV0110B.PSV0110L.P0101B.P0101F.P0102B.P0102F.P0103F .P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO.PP0110FSO.CT0110T.PP0110FSO.PP0110FM.PP0110L
12)	PSV0110PB.PP0110FO.PSV0110ISO.PSV0110S.PSV0110B.PSV0110ISC.PSV0110L.P0101B.P0101F.P0102B.P0102F.P0103F .P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO.PP0110FSO.CT0110T.PP0110FSO.PP0110FM.PP0110L
13)	PSV0110L.PP0110FO.PSV0110ISO.PSV0110S.PSV0110PB.PSV0110ISC.PSV0110B.P0101B.P0101F.P0102B.P0102F.P0103F .P0115B.P0115F.P0116B.P0116F.P0117B.IVP0110FO.PP0110FSO.CT0110T.PP0110FSO.PP0110FM.PP0110L
14)	IVP0110S.PP0110FO.PSV0110ISC.PSV0110B.P0101B.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0116B .P0116F.P0117B.IVP0110FO.IVP0110FC.IVP0110B.IVP0110PB.IVP0110L.CT0110T.PP0110FSO.PP0110FM.PP0110L
15)	IVP0110FO.P0103PB.PP0110FO.IVP0110FC.IVP0110PB.IVP0110B.IVP0110S.IVP0110L.P0103B.P0103F.P0103L.P0101B .P0101F.P0102B.P0102F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
16)	IVP0110FO.P0104PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0104B.P0104F.P0104L.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
17)	IVP0110FO.P0105PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0105B.P0105F.P0105L.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
18)	IVP0110FO.P0106PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0106B.P0106F.P0106L.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
19)	IVP0110FO.P0113PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0113B.P0113F.P0113L.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
20)	IVP0110FO.P0114PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0114B.P0114F.P0114L.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
21)	IVP0110FO.BP0110PB.PP0110FO.BP0110B.BP0110L.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110PB.P0101B.P0101F .P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
22)	CT0110T.P0103PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0103B.P0103F.P0103L.P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
23)	CT0110T.P0104PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0104B.P0104F.P0104L.PP0110FSO.PP0110FM.PP0110L .P0101B.P0101F.P0102B.P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B
24)	CT0110T.P0105PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0105B.P0105F.P0105L.P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
25)	CT0110T.P0106PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0106B.P0106F.P0106L .P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
26)	CT0110T.P0113PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0113B.P0113F.P0113L.P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
27)	CT0110T.P0114PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0114B.P0114F.P0114L.P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
28)	CT0110T.BP0110PB.PP0110FO.BP0110B.BP0110L.IVP0110FC.IVP0110B.CT0110F.P0101B.P0101F.P0102B.P0102F .P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L
29)	CT0110T.IVP0110PB.PP0110FO.IVP0110FC.IVP0110B.IVP0110S.IVP0110L.IVP0110FO.CT0110F.P0101B.P0101F.P0102B .P0102F.P0103F.P0115B.P0115F.P0116B.P0116F.P0117B.PSV0110ISC.PSV0110B.PP0110FSO.PP0110FM.PP0110L

Table D.39: Prime implicants for partial flow PSV0110 when low flow is required in the DORMANT operating mode

D.1.20 Partial Flow at IVP0120 when Low Flow is Required

PFPSV0120LFA = $\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119FB}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{IVP0120FO}}$
$.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.\overline{\mathrm{CT0120T}}.(\mathrm{P0109PB}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109L}}$
$+\mathrm{P0110PB}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110L}} + \mathrm{P0111PB}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111L}}$
$+\mathrm{P0112PB}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0111L}}$
$+\mathrm{P0113PB}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113L}}$
$+\mathrm{P0114PB}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114L}}$
$+\mathrm{IVP0120S}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120L}}$
$+\mathrm{IVP0120PB}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120L}} + \mathrm{BP0120PB}.\overline{\mathrm{BP0120L}}.\overline{\mathrm{BP0120B}})$
$+(\mathrm{P0109B}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}} + \mathrm{P0110B}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}}$
$+\mathrm{P0111B}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111L}} + \mathrm{P0112B}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0112L}}$
$+\mathrm{P0113B}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}} + \mathrm{P0114B}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{P0114L}}$
$+\mathrm{IVP0120S}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120L}}$
$+\mathrm{IVP0120B}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120L}}$
$+\mathrm{IVP0120FC}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{BP0120B}}.\overline{\mathrm{BP0120PB}}.\overline{\mathrm{BP0120L}})$
$.(\mathrm{P0107PB}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107L}} + \mathrm{P0107L}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107L}}$
$+\mathrm{P0108PB}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108L}} + \mathrm{P0108L}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108L}}$
$+\mathrm{P0118PB}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0118L}} + \mathrm{P0118L}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0118L}}$
$+\mathrm{P0119PB}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119L}} + \mathrm{P0119L}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0119L}}$
$+\mathrm{P0120PB}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0120F}}.\overline{\mathrm{P0120L}} + \mathrm{P0109L}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109L}}$
$+\mathrm{PP0120FM}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120L}} + \mathrm{PP0120L}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}}$
$+(\mathrm{PSV0120S}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120L}} + \mathrm{PSV0120PB}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}$
$+\mathrm{PSV0120L}.\overline{\mathrm{PSV0120PB}}.\overline{\mathrm{PSV0120S}}).(\overline{\mathrm{PSV0120B}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120ISO}})$
$+(\overline{\mathrm{P0109B}}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{CT0120F}}).(\mathrm{P0110L}.\overline{\mathrm{P0110PB}}$
$+\mathrm{P0111L}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111PB}} + \mathrm{P0112L}.\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}}$
$+\mathrm{P0113L}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{BP0120B}}$
$+\mathrm{BP0120L}.\overline{\mathrm{BP0120B}}.\overline{\mathrm{BP0120PB}}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}})).(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}})$

PFPSV0120LFD = $\mathrm{PP0120FO}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}}\overline{\mathrm{PP0120L}}.(\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0119B}}$
$.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.(\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{CT0120T}} + \mathrm{P0118PB}.\overline{\mathrm{P0118L}}$
$+\mathrm{P0118L}.\overline{\mathrm{P0118PB}} + \mathrm{P0119PB}.\overline{\mathrm{P0119L}} + \mathrm{P0119L}.\overline{\mathrm{P0119PB}} + \mathrm{P0120PB}.\overline{\mathrm{P0120L}}$
$+\mathrm{P0107PB}.\overline{\mathrm{P0107L}} + \mathrm{P0107L}.\overline{\mathrm{P0107PB}} + \mathrm{P0108PB}.\overline{\mathrm{P0108L}} + \mathrm{P0108L}.\overline{\mathrm{P0108PB}}$
$+\mathrm{P0109PB}.\overline{\mathrm{P0109L}} + \mathrm{P0109L}.\overline{\mathrm{P0109PB}} + \mathrm{PSV0120S}.\overline{\mathrm{PSV0120ISO}}.\overline{\mathrm{PSV0120L}}$
$+\mathrm{PSV0120L}.\overline{\mathrm{PSV0120ISO}}.\overline{\mathrm{PSV0120S}} + \mathrm{PSV0120ISO}.\overline{\mathrm{PSV0120S}}.\overline{\mathrm{PSV0120L}}$
$+\mathrm{IVP0120S}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120L}})$
$+(\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{PSV0120ISC}}$
$.\overline{\mathrm{PSV0120B}}.((\mathrm{IVP0120FO}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120L}}$
$+\mathrm{CT0120T}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120L}}.\overline{\mathrm{CT0120F}})$
$.(\mathrm{P0109PB}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109L}} + \mathrm{P0110PB}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110L}}$
$+\mathrm{P0111PB}.\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111F}}.\overline{\mathrm{P0111L}} + \mathrm{P0112PB}.\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112F}}.\overline{\mathrm{P0112L}}$
$+\mathrm{P0113PB}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113L}} + \mathrm{P0114PB}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114L}}$
$+\mathrm{BP0120PB}.\overline{\mathrm{BP0120B}}.\overline{\mathrm{BP0120L}})) + \mathrm{IVP0120PB}.\mathrm{CT0120T}.\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{IVP0120FO}}.\overline{\mathrm{IVP0120S}}$
$.\overline{\mathrm{IVP0120L}}.\overline{\mathrm{CT0120F}}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0118B}}.\overline{\mathrm{P0118F}}.\overline{\mathrm{P0119B}}.\overline{\mathrm{P0119F}}.\overline{\mathrm{P0120B}}.\overline{\mathrm{P0109F}}$
$.\overline{\mathrm{PSV0120ISC}}.\overline{\mathrm{PSV0120B}}.(\mathrm{DORMANT}.\overline{\mathrm{ACTIVE}}))$

Number	Prime Implicants
1)	P0109PB.P0109F.P0109B.P0109L.P0107B.P0107F.P0108B.P0108F.P0118B.P0118F.P0119B.P0119F.P0120B .IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
2)	P0110PB.P0110F.P0110B.P0110L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
3)	P0111PB.P0111F.P0111B.P0111L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
4)	P0112PB.P0112F.P0112B.P0112L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
5)	P0113PB.P0113F.P0113B.P0113L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
6)	P0114PB.P0114F.P0114B.P0114L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
7)	IVP0120S.IVP0120FO.IVP0120B.IVP0120FC.IVP0120PB.IVP0120L.P0107B.P0107F.P0108B.P0108F.P0109F .P0118B.P0118F.P0119B.P0119F.P0120B.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
8)	IVP0120PB.IVP0120FO.IVP0120FO.IVP0120S.IVP0120B.IVP0120L.P0107B.P0107F.P0108B.P0108F.P0109F .P0118B.P0118F.P0119B.P0119F.P0120B.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
9)	BP0120PB.BP0120L.BP0120PB.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .P0120B.IVP0120FOPP0120FSO.PSV0120ISC.PSV0120B.CT0120T

Table D.40: Prime implicants for unexpected partial flow at IVP0120 when low flow is required in the ACTIVE operating mode -Table 2

Number	Prime Implicants			
1)	P0109B.P0109F.P0109PB.P0109L		1)	P0107PB.P0107B.P0107F.P0107L
2)	P0110B.P0110F.P0110PB.P0110L		2)	P0107L.P0107B.P0107F.P0107PB
3)	P0111B.P0111F.P0111PB.P0111L		3)	P0108PB.P0108B.P0108F.P0108L
4)	P0112B.P0112F.P0112PB.P0112L		4)	P0108L.P0108B.P0108F.P0108PB
5)	P0113B.P0113F.P0113PB.P0113L		5)	P0118PB.P0118B.P0118F.P0118L
6)	P0114B.P0114F.P0114PB.P0114L		2)	P0118L.P0118B.P0118F.P0118PB
7)	IVP0120FC.IVP0120FO.IVP0120B .IVP0120PB.IVP0120S.IVP0120L		7)	P0119PB.P0119B.P0119F.P0119L
			8)	P0119L.P0119B.P0119F.P0119PB
8)	IVP0120B.IVP0120FO.IVP0120FC .IVP0120PB.IVP0120S.IVP0120L		9)	P0120PB.P0120B.P0120F.P0120L
		AND	10)	PSV0120S.PSV0120ISC.PSV0120ISO.PSV0120B.PSV0120PB.PSV0120L
9)	BP0120B.BP0120PB.BP0120L		11)	PSV0120PB.PSV0120ISC.PSV0120ISO.PSV0120B.PSV0120S.PSV0120L
			12)	PSV0120L.PSV0120ISC.PSV0120ISO.PSV0120B.PSV0120PB.PSV0120S
			13)	PP0120FM.PP0120FSO.PP0120FO.PP0120L
			14)	PP0120L.PP0120FSO.PP0120FO.PP0120FM
			15)	P0109L.P0109B.P0109F.P0109PB
			16)	P0110L.P0110B.P0110F.P0110PB.P0109B.IVP0120B.IVP0120FC.CT0120F
			17)	P0111L.P0111B.P0111F.P0111PB.P0109B.P0110B.P0110F.IVP0120B .IVP0120FC.CT0120F
			18)	P0112L.P0112B.P0112F.P0112PB.P0109B.P0110B.P0110F.P0111B .P0111F.IVP0120B.IVP0120FC.CT0120F.BP0120B
			19)	P0113L.P0113B.P0113F.P0113PB.P0109B.P0110B.P0110F.P0111B .P0111F.P0112B.P0112F.IVP0120B.IVP0120FC.CT0120F.BP0120B
			20)	BP0120L.BP0120B.BP0120PB.P0109B.P0110B.P0110F.P0111B .P0111F.IVP0120B.IVP0120FC.CT0120F

Table D.41: Prime implicants for unexpected partial flow at IVP0120 when low flow is required in the ACTIVE operating mode -Table 2

Number	Prime Implicants
1)	P0118PB.PP0120FO.P0118F.P0118B.P0118L.P0107B.P0107F.P0108B.P0108F .P0109F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
2)	P0118L.PP0120FO.P0118B.P0118PB.P0118F.P0107B.P0107F.P0108B.P0108F .P0109F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
3)	P0118PB.PP0120FO.P0119F.P0119B.P0119L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0120B .IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
4)	P0118L.PP0120FO.P0119B.P0119PB.P0119F.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0120B .IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
5)	P0118PB.PP0120FO.P0120F.P0120B.P0120L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F .IVP0120FO.PP0120FSO.PSV0110ISC.PSV0120B.CT0120T.PP0110FSO.PP0120FM.PP0120L
6)	P0107PB.PP0120FO.P0107F.P0107B.P0107L.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO .PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
7)	P0107L.PP0120FO.P0107B.P0107PB.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO .PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
8)	P0108PB.PP0120FO.P0108F.P0108B.P0108L.P0107B.P0107F.P0109F.P0118B.P0118F.P0110B.P0119F.P0120B.IVP0120FO .PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
9)	P0108L.PP0120FO.P0108B.P0108PB.P0108F.P0107B.P0107F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO .PP0120FSO.PSV0120ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
10)	P0109L.PP0120FO.P0109B.P0109PB.P0109F.P0107B.P0107F.P0108B.P0108F.P0118B.P0118F.P0119B.P0119F.P0120B .IVP0120FO.PP0120FSO.PSV010ISC.PSV0120B.CT0120T.PP0120FSO.PP0120FM.PP0120L
11)	PSV0120S.PP0120FO.PSV0120ISO.PSV0120ISC.PSV0120PB.PSV0120B.PSV0120L.P0107B.P0107F.P0108B.P0108F.P0109F .P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.CT0120T.PP0120FSO.PP0120FM.PP0120L
12)	PSV0120PB.PP0120FO.PSV0120ISO.PSV0120S.PSV0120B.PSV0120ISC.PSV0120L.P0107B.P0107F.P0108B.P0108F.P0109F .P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.CT0120T.PP0120FSO.PP0120FM.PP0120L
13)	PSV0120L.PP0120FO.PSV0120ISO.PSV0120S.PSV0120PB.PSV0120ISC.PSV0120B.P0107B.P0107F.P0108B.P0108F.P0109F .P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.CT0120T.PP0120FSO.PP0120FM.PP0120L
14)	IVP0120S.PP0120FO.PSV0120ISC.PSV0120B.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B .P0119F.P0120B.IVP0120FO.IVP0120FC.IVP0120B.IVP0120PB.IVP0120L.CT0120T.PP0120FSO.PP0120FM.PP0120L
15)	IVP0120FO.P0109PB.PP0120FO.IVP0120FC.IVP0120PB.IVP0120B.IVP0120S.IVP0120L.P0109B.P0109F.P0109L.P0107B .P0107F.P0108B.P0108F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B.PP0120FSO.PP0120FM.PP0120L
16)	IVP0120FO.P0110PB.PP0120FO.IVP0120FC.IVP0120B.IVP0110S.IVP0120L.IVP0120PB.P0110B.P0110F.P0110L.P0107B .P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B.PP0120FSO.PP0120FM.PP0120L
17)	IVP0120FO.P0111PB.PP0120FO.IVP0120FC.IVP0120B.IVP0120S.IVP0120L.IVP0120PB.P0111B.P01118F.P0111L.P0107B.P0107F .P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0118F.P0120B.PSV0120ISC.PSV0120B.PP0120FSO.PP0120FM.PP0120L
18)	IVP0120FO.P0112PB.PP0120FO.IVP0120FC.IVP0120B.IVP0120S.IVP0120L.IVP0120PB.P0112B.P0112F.P0112L.P0107B .P0107F .P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B.PP0120FSO.PP0120FM.PP0120L
19)	IVP0120FO.P0113PB.PP0120FO.IVP0120FC.IVP0110B.IVP0120S.IVP0110L.IVP0110PB.P0113B.P0113F.P0113L.P0107B.P0107F .P0102B.P0102F.P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
20)	IVP0120FO.P0114PB.PP0120FO.IVP0110FC.IVP0110B.IVP0120S.IVP0110L.IVP0110PB.P0114B.P0114F.P0114L.P0107B.P0107F .P0102B.P0102F.P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
21)	IVP0120FO.BP0120PB.PP0120FO.BP0110B.BP0110L.IVP0120FC.IVP0110B.IVP0110S.IVP0120L.IVP0110PB.P0101B.P0107F .P0102B.P0102F.P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
22)	CT0120T.P0109PB.PP0120FO.IVP0110FC.IVP0110B.CT0120F.P0103B.P0103F.P0109L.P0101B.P0101F.P0108B.P0102F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
23)	CT0120T.P0110PB.PP0110FO.IVP0110FC.IVP0110B.CT0110F.P0104B.P0104F.P0110L.PP0110FSO.PP0110FM.PP0120L .P0107B.P0101F.P0102B.P0108F.P0103F.P0115B.P0118F.P0116B.P0116F.P0120B.PSV0110ISC.PSV0110B
24)	CT0120T.P0111PB.PP0120FO.IVP0110FC.IVP0110B.CT0120F.P0105B.P0105F.P0111L.P0101B.P0101F.P0108B.P0102F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
25)	CT0120T.P0112PB.PP0120FO.IVP0110FC.IVP0110B.CT0120F.P0106B.P0106F.P0112L .P0101B.P0101F.P0108B.P0102F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
26)	CT0120T.P0113PB.PP0120FO.IVP0110FC.IVP0110B.CT0120F.P0113B.P0113F.P0113L.P0101B.P0101F.P0108B.P0102F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
27)	CT0120T.P0114PB.PP0120FO.IVP0110FC.IVP0110B.CT0120F.P0114B.P0114F.P0114L.P0101B.P0101F.P0108B.P0102F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
28)	CT0120T.BP0120PB.PP0120FO.BP0110B.BP0110L.IVP0120FC.IVP0110B.CT0110F.P0107B.P0101F.P0102B.P0107F .P0109F.P0115B.P0115F.P0119B.P0116F.P0117B.PSV0120ISC.PSV0110B.PP0110FSO.PP0120FM.PP0110L
29)	CT0120T.IVP0120PB.PP0120FO.IVP0110FC.IVP0110B.IVP0120S.IVP0110L.IVP0110FO.CT0120F.P0101B.P0101F.P0108B .P0108F.P0103F.P0115B.P0118F.P0116B.P0116F.P0120B.PSV0110ISC.PSV0110B.PP0120FSO.PP0110FM.PP0110L

Table D.42: Prime implicants for partial flow at PSV0120 when low flow is required in the DORMANT operating mode

D.1.21 Partial Flow at PSV0110 when Flow is Required

$$
\begin{aligned}
\mathrm{PFPSV0110F} = {} & (\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0103F}} \\
& .\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PP0110FSO}}.(\mathrm{IVP0110FO}.\overline{\mathrm{CT0110T}}.(\mathrm{PP0110FM}.\overline{\mathrm{PP0110FO}} \\
& +\mathrm{PP0110L}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110FSO}} + \mathrm{P0115PB}.\overline{\mathrm{P0115L}} + \mathrm{P0115L}.\overline{\mathrm{P0115PB}} \\
& +\mathrm{P0116PB}.\overline{\mathrm{P0116L}} + \mathrm{P0116L}.\overline{\mathrm{P0116PB}} + \mathrm{P0117PB}.\overline{\mathrm{P0117L}} + \mathrm{P0101PB}.\overline{\mathrm{P0101L}} + \mathrm{P0101L}.\overline{\mathrm{P0101PB}} \\
& +\mathrm{P0102PB}.\overline{\mathrm{P0102L}} + \mathrm{P0102L}.\overline{\mathrm{P0102PB}} + \mathrm{P0103PB}.\overline{\mathrm{P0103L}} + \mathrm{P0103L}.\overline{\mathrm{P0103PB}} \\
& +\mathrm{PSV0110S}.\overline{\mathrm{PSV0110ISO}}.\overline{\mathrm{PSV0110L}} + \mathrm{PSV0110L}.\overline{\mathrm{PSV0110ISO}}.\overline{\mathrm{PSV0110S}} \\
& +\mathrm{PSV0110ISO}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110L}} + \mathrm{IVP0110S}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110L}}) \\
& +(\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{PSV0110ISC}} \\
& .\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PP0110FSO}}).((\mathrm{IVP0110FO}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}} \\
& +\mathrm{CT0110T}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{CT0110F}}) \\
& .(\mathrm{P0103PB}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}} + \mathrm{P0104PB}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104L}} \\
& +\mathrm{P0105PB}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105L}} + \mathrm{P0106PB}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106F}}.\overline{\mathrm{P0106L}} \\
& +\mathrm{P0113PB}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113L}} + \mathrm{P0114PB}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114F}}.\overline{\mathrm{P0114L}} \\
& +\mathrm{BP0110PB}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{BP0110L}})) + \mathrm{IVP0110PB}.\mathrm{CT0110T}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}} \\
& .\overline{\mathrm{IVP0110L}}.\overline{\mathrm{CT0110F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0103F}} \\
& .\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PP0110FSO}}).(\mathrm{ACTIVE}.\overline{\mathrm{DORMANT}})
\end{aligned}
$$

Number	Prime Implicants
1)	$\mathrm{PP0110FM}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
2)	$\mathrm{PP0110L}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
3)	$\mathrm{P0115PB}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
4)	$\mathrm{P0115L}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
5)	$\mathrm{P0116PB}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
6)	$\mathrm{P0116L}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
7)	$\mathrm{P0117PB}.\overline{\mathrm{P0117F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
8)	$\mathrm{P0101PB}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
9)	$\mathrm{P0101L}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
10)	$\mathrm{P0102PB}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
11)	$\mathrm{P0102L}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102PB}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
12)	$\mathrm{P0103L}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{CT0110T}}$
13)	$\mathrm{PSV0110S}.\overline{\mathrm{PSV0110ISO}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110T}}$
14)	$\mathrm{PSV0110PB}.\overline{\mathrm{PSV0110ISO}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110T}}$
15)	$\mathrm{PSV0110L}.\overline{\mathrm{PSV0110ISO}}.\overline{\mathrm{PSV0110S}}.\overline{\mathrm{PSV0110PB}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{CT0110T}}$
16)	$\mathrm{IVP0110S}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{CT0110T}}$
17)	$\mathrm{IVP0110FO}.\mathrm{P0103PB}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}$
18)	$\mathrm{IVP0110FO}.\mathrm{P0104PB}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}$
19)	$\mathrm{IVP0110FO}.\mathrm{P0105PB}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105F}}.\overline{\mathrm{P0105L}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{PSV0110ISC}}.\overline{\mathrm{PSV0110B}}$

Table D.43: Prime implicants for partial flow at PSV0110 when flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
20)	IVP0110FO.P0106PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
21)	IVP0110FO.P0113PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
22)	IVP0110FO.P0114PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114F}}$.$\overline{\text{P0114L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
23)	IVP0110FO.BP0110PB.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110L}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{IVP0110PB}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
24)	CT0110T.P0103PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0103B}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0103L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
25)	CT0110T.P0104PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0104B}}$.$\overline{\text{P0104F}}$.$\overline{\text{P0104L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
26)	CT0110T.P0105PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0105B}}$.$\overline{\text{P0105F}}$.$\overline{\text{P0105L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
27)	CT0110T.P0106PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0106B}}$.$\overline{\text{P0106F}}$.$\overline{\text{P0106L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
28)	CT0110T.P0113PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
29)	CT0110T.P0114PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0114B}}$.$\overline{\text{P0114F}}$.$\overline{\text{P0114L}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
30)	CT0110T.BP0110PB.$\overline{\text{BP0110B}}$.$\overline{\text{BP0110L}}$.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$
31)	CT0110T.IVP0110PB.$\overline{\text{IVP0110FC}}$.$\overline{\text{IVP0110B}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0110L}}$.$\overline{\text{IVP0110FO}}$.$\overline{\text{CT0110F}}$.$\overline{\text{P0101B}}$.$\overline{\text{P0101F}}$.$\overline{\text{P0102B}}$.$\overline{\text{P0102F}}$.$\overline{\text{P0103F}}$.$\overline{\text{P0115B}}$.$\overline{\text{P0115F}}$.$\overline{\text{P0116B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0117B}}$.$\overline{\text{PSV0110ISC}}$.$\overline{\text{PSV0110B}}$

Table D.44: Prime implicants for partial flow at PSV0110 when flow is required in the ACTIVE operating mode - Table 2

D.1.22 Partial Flow at PSV0120 when Flow is Required

PFPSV0120LFA = ($\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0118B}}$.$\overline{\text{P0118F}}$.$\overline{\text{P0119B}}$.$\overline{\text{P0119F}}$.$\overline{\text{P0120B}}$.$\overline{\text{P0109F}}$
.$\overline{\text{PSV0120ISC}}$.$\overline{\text{PSV0120B}}$.$\overline{\text{PP0120FSO}}$.($\overline{\text{IVP0120FO}}$.$\overline{\text{CT0120T}}$.(PP0120FM.$\overline{\text{PP0120FO}}$
+PP0120L.$\overline{\text{PP0120FO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0110FSO}}$ + P0118PB.$\overline{\text{P0118L}}$ + P0118L.$\overline{\text{P0115PB}}$
+P0119PB.$\overline{\text{P0119L}}$ + P0119L.$\overline{\text{P0119PB}}$ + P0120PB.$\overline{\text{P0120L}}$ + P0107PB.$\overline{\text{P0107L}}$ + P0101L.$\overline{\text{P0107PB}}$
+P0108PB.$\overline{\text{P0108L}}$ + P0108L.$\overline{\text{P0108PB}}$ + P0109PB.$\overline{\text{P0109L}}$ + P0109L.$\overline{\text{P0109PB}}$
+PSV0120S.$\overline{\text{PSV0120ISO}}$.$\overline{\text{PSV0120L}}$ + PSV0120L.$\overline{\text{PSV0120ISO}}$.$\overline{\text{PSV0120S}}$
+PSV0120ISO.$\overline{\text{PSV0120S}}$.$\overline{\text{PSV0120L}}$ + IVP0120S.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120I}}$
+($\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0118B}}$.$\overline{\text{P0118F}}$.$\overline{\text{P0119B}}$.$\overline{\text{P0119F}}$.$\overline{\text{P0120B}}$.$\overline{\text{P0109F}}$.$\overline{\text{PSV0120ISC}}$
.$\overline{\text{PSV0120B}}$.$\overline{\text{PP0120FSO}}$).((IVP0120FO.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0120S}}$.$\overline{\text{IVP0120L}}$
+CT0120T.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120PB}}$.$\overline{\text{IVP0110S}}$.$\overline{\text{IVP0120L}}$.$\overline{\text{CT0120F}}$)
.(P0109PB.$\overline{\text{P0109B}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0109L}}$ + P0110PB.$\overline{\text{P0110B}}$.$\overline{\text{P0110F}}$.$\overline{\text{P0110L}}$
+P0111PB.$\overline{\text{P0111B}}$.$\overline{\text{P0111F}}$.$\overline{\text{P0111L}}$ + P0112PB.$\overline{\text{P0112B}}$.$\overline{\text{P0112F}}$.$\overline{\text{P0112L}}$
+P0113PB.$\overline{\text{P0113B}}$.$\overline{\text{P0113F}}$.$\overline{\text{P0113L}}$ + P0114PB.$\overline{\text{P0114B}}$.$\overline{\text{P0114F}}$.$\overline{\text{P0114L}}$
+BP0120PB.$\overline{\text{BP0120B}}$.$\overline{\text{BP0120L}}$)) + IVP0120PB.CT0120T.$\overline{\text{IVP0120FC}}$.$\overline{\text{IVP0120B}}$.$\overline{\text{IVP0120FO}}$.$\overline{\text{IVP0120S}}$
.$\overline{\text{IVP0120L}}$.$\overline{\text{CT0120F}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0118B}}$.$\overline{\text{P0118F}}$.$\overline{\text{P0119B}}$.$\overline{\text{P0119F}}$.$\overline{\text{P0120B}}$.$\overline{\text{P0109F}}$
.$\overline{\text{PSV0120ISC}}$.$\overline{\text{PSV0120B}}$.$\overline{\text{PP0120FSO}}$).(ACTIVE.$\overline{\text{DORMANT}}$)

Number	Prime Implicants
1)	PP0120FM.$\overline{\text{PP0120FO}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{PP0120L}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0109F}}$.$\overline{\text{P0118B}}$.$\overline{\text{P0118F}}$.$\overline{\text{P0119B}}$.$\overline{\text{P0116F}}$.$\overline{\text{P0120B}}$.$\overline{\text{IVP0120FO}}$.$\overline{\text{PSV0120ISC}}$.$\overline{\text{PSV0120B}}$.$\overline{\text{CT0120T}}$
2)	PP0120L.$\overline{\text{PP0120FO}}$.$\overline{\text{PP0110FM}}$.$\overline{\text{PP0120FSO}}$.$\overline{\text{P0107B}}$.$\overline{\text{P0107F}}$.$\overline{\text{P0108B}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0108F}}$.$\overline{\text{P0118B}}$.$\overline{\text{P0118F}}$.$\overline{\text{P0119B}}$.$\overline{\text{P0119F}}$.$\overline{\text{P0120B}}$.$\overline{\text{IVP0120FO}}$.$\overline{\text{PSV0120ISC}}$.$\overline{\text{PSV0120B}}$.$\overline{\text{CT0120T}}$

Table D.45: Prime implicants for partial flow at PSV0110 when flow is required in the ACTIVE operating mode - Table 1

Number	Prime Implicants
3)	P0118PB.P0118F.P0118B.P0118L.P0107B.P0108F.P0108B.P0108F.P0109F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
4)	P0118L.P0118B.P0118PB.P0118F.P0107B.P0101F.P0108B.P0108F.P0109F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
5)	P0119PB.P0119F.P0119B.P0119L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0120B.IVP0120FO.PP0110FSO.PSV0120ISC.PSV0120B.CT0120T
6)	P0119L.P0119B.P0119PB.P0119F.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
7)	P0120PB.P0120F.P0117B.P0120L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
8)	P0107PB.P0107F.P0107B.P0107L.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
9)	P0107L.P0107B.P0107PB.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
10)	P0108PB.P0102F.P0108B.P0108L.P0107B.P0107F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
11)	P0108L.P0102B.P0108PB.P0108F.P0107B.P0107F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
12)	P0109L.P0103B.P0109PB.P0109F.P0107B.P0107F.P0108B.P0108F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.PSV0120ISC.PSV0120B.CT0120T
13)	PSV0120S.PSV0110ISO.PSV0120ISC.PSV0120PB.PSV0120B.PSV0120L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.CT0120T
14)	PSV0120PB.PSV0120ISO.PSV0120S.PSV0120B.PSV0120ISC.PSV0120L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0110B.IVP0110FO.PP0120FSO.CT0110T
15)	PSV0120L.PSV0110ISO.PSV0110S.PSV0120PB.PSV0110ISC.PSV0110B.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.CT0120T
16)	IVP0120S.PSV0120ISC.PSV0120B.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.IVP0120FO.PP0120FSO.IVP0120FC.IVP0120B.IVP0120PB.IVP0120L.CT0120T
17)	IVP0120FO.P0109PB.IVP0120FC.IVP0120PB.IVP0120B.IVP0120S.IVP0120L.P0109B.P0193F.P0109L.P0107B.P0107F.P0108B.P0108F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
18)	IVP0120FO.P0110PB.IVP0120FC.IVP0120B.IVP0120S.IVP01210L.IVP0120PB.P0110B.P0110F.P0110L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
19)	IVP0120FO.P0111PB.IVP0120FC.IVP0120B.IVP0120S.IVP0120L.IVP0120PB.P0111B.P0111F.P0111L.P0101B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
20)	IVP0120FO.P0112PB.IVP0120FC.IVP0120B.IVP0120S.IVP0120L.IVP0120PB.P0112B.P0112F.P0112L.P0107B.P0101F.P0102B.P0108F.P0109F.P0115B.P0119F.P0119B.P0116F.P0120B.PSV0120ISC.PSV0110B
21)	IVP0120FO.P0113PB.IVP0120FC.IVP0110B.IVP0120S.IVP0120L.IVP0120PB.P0113B.P0113F.P0113L.P0101B.P0107F.P0108B.P0102F.P0103F.P0118B.P0115F.P0116B.P0119F.P0117B.PSV0110ISC.PSV0130B
22)	IVP0120FO.P0114PB.IVP0110FC.IVP0130B.IVP0120S.IVP0110L.IVP0130PB.P0114B.P0114F.P0114L.P0107B.P0101F.P0108B.P0108F.P0109F.P0118B.P0118F.P01169.P0119F.P0120B.PSV0120ISC.PSV0130B
23)	IVP0120FO.BP0120PB.BP0120B.BP0130L.IVP0120FC.IVP0120B.IVP0130S.IVP0120L.IVP0120PB.P0101B.P0101F.P0102B.P0108F.P0103F.P0115B.P0118F.P0116B.P0116F.P0120B.PSV0110ISC.PSV0110B
24)	CT0120T.P0109PB.IVP0110FC.IVP0110B.CT0120F.P0103B.P0103F.P0109L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
25)	CT0120T.P0110PB.IVP0120FC.IVP0120B.CT0120F.P0110B.P0120F.P0110L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
26)	CT0120T.P0111PB.IVP0120FC.IVP0120B.CT0120F.P0111B.P0111F.P0111L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
27)	CT0120T.P0112PB.IVP0120FC.IVP0120B.CT0120F.P0112B.P0112F.P0112L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
28)	CT0120T.P0113PB.IVP0120FC.IVP0120B.CT0110F.P0113B.P0113F.P0113L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
29)	CT0120T.P0114PB.IVP0120FC.IVP0120B.CT0120F.P0114B.P0114F.P0114L.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
30)	CT0120T.BP0120PB.BP0120B.BP0120L.IVP0120FC.IVP01210B.CT0120F.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B
31)	CT0120T.IVP0120PB.IVP0120FC.IVP0120B.IVP0120S.IVP0120L.IVP0120FO.CT0120F.P0107B.P0107F.P0108B.P0108F.P0109F.P0118B.P0118F.P0119B.P0119F.P0120B.PSV0120ISC.PSV0120B

Table D.46: Prime implicants for partial flow at PSV0110 when flow is required in the ACTIVE operating mode - Table 2

D.2 Success Trees

D.2.1 Working Low Flow at IVP0130

$$\mathrm{SUCCESSLFIVP0130} = \overline{\mathrm{IVP0130FO}}.\overline{\mathrm{CT0130T}}.\overline{\mathrm{IVP0130S}}$$

D.2.2 Working Flow at IVP0110

$$\begin{aligned}\mathrm{SUCCESSHFIVP0110} = \; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}} \\ & .\overline{\mathrm{P0102L}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104F}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0104L}} \\ & .\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}} \\ & .\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{CT0110F}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}}.\overline{\mathrm{BP0110B}} \\ & .\overline{\mathrm{BP0110PB}}.\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}\end{aligned}$$

D.2.3 Working Low Flow at IVP0110

$$\begin{aligned}\mathrm{SUCCESSLFIVP0110} = \; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{IV0110FO}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{IVP0110S}} \\ & +\overline{\mathrm{ACTIVE}}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{IV0110FO}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{IVP0110S}}\end{aligned}$$

D.2.4 Working Flow at IVP0120

$$\begin{aligned}\mathrm{SUCCESSHFIVP0120} = \; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{P0107B}}.\overline{\mathrm{P0107F}}.\overline{\mathrm{P0107PB}}.\overline{\mathrm{P0107L}}.\overline{\mathrm{P0108B}}.\overline{\mathrm{P0108F}}.\overline{\mathrm{P0108PB}} \\ & .\overline{\mathrm{P0108L}}.\overline{\mathrm{P0109B}}.\overline{\mathrm{P0109F}}.\overline{\mathrm{P0109PB}}.\overline{\mathrm{P0109L}}.\overline{\mathrm{P0110B}}.\overline{\mathrm{P0110F}}.\overline{\mathrm{P0110PB}}.\overline{\mathrm{P0110L}} \\ & .\overline{\mathrm{P0111B}}.\overline{\mathrm{P0111PB}}.\overline{\mathrm{P0112B}}.\overline{\mathrm{P0112PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}} \\ & .\overline{\mathrm{IVP0120FC}}.\overline{\mathrm{IVP0120B}}.\overline{\mathrm{CT0120F}}.\overline{\mathrm{IVP0120PB}}.\overline{\mathrm{IVP0120S}}.\overline{\mathrm{IVP0120L}}.\overline{\mathrm{BP0120B}} \\ & .\overline{\mathrm{BP0120PB}}.\overline{\mathrm{PP0120FSO}}.\overline{\mathrm{PP0120FM}}.\overline{\mathrm{PP0120L}}\end{aligned}$$

D.2.5 Working Low Flow at IVP0120

$$\begin{aligned}\mathrm{SUCCESSLFIVP0120} \;=\; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{IV0120FO}}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120S}} \\ & +\overline{\mathrm{ACTIVE}}.\overline{\mathrm{PP0120FO}}.\overline{\mathrm{IV0120FO}}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120S}}\end{aligned}$$

D.2.6 Working Flow at IVP0130

$$\mathrm{SUCCESSHFIVP0130} \;=\; \overline{\mathrm{DORMANT}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113F}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0113L}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114F}}$$

D.2.7 Working Low Flow at IVP0130

$$\begin{aligned}\mathrm{SUCCESSLFIVP0130} \;=\; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{IV0110FO}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IV0120FO}}.\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120S}} \\ & +\overline{\mathrm{ACTIVE}}.\overline{\mathrm{PP0110FO}}.\overline{\mathrm{PP0120FO}}.\overline{\mathrm{IV0110FO}}.\overline{\mathrm{CT0110T}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IV0120FO}} \\ & .\overline{\mathrm{CT0120T}}.\overline{\mathrm{IVP0120S}}\end{aligned}$$

D.2.8 Working Flow at IVP0111

$$\begin{aligned}\mathrm{SUCCESSHFIVP0111} \;=\; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{P0101B}}.\overline{\mathrm{P0101F}}.\overline{\mathrm{P0101PB}}.\overline{\mathrm{P0101L}}.\overline{\mathrm{P0102B}}.\overline{\mathrm{P0102F}}.\overline{\mathrm{P0102PB}} \\ & .\overline{\mathrm{P0102L}}.\overline{\mathrm{P0103F}}.\overline{\mathrm{P0103L}}.\overline{\mathrm{P0115B}}.\overline{\mathrm{P0115F}}.\overline{\mathrm{P0115PB}}.\overline{\mathrm{P0115L}}.\overline{\mathrm{P0116B}}.\overline{\mathrm{P0116F}} \\ & .\overline{\mathrm{P0116PB}}.\overline{\mathrm{P0116L}}.\overline{\mathrm{P0117B}}.\overline{\mathrm{P0117PB}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}} \\ & .\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}}.\overline{\mathrm{P0106PB}}.\overline{\mathrm{IVP0110FO}}.\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110L}} \\ & .\overline{\mathrm{PP0110FSO}}.\overline{\mathrm{PP0110FM}}.\overline{\mathrm{PP0110L}}.\overline{\mathrm{PSV0110B}}.\overline{\mathrm{PSV0110L}}.\overline{\mathrm{PSV0110ISC}}\end{aligned}$$

D.2.9 Working Low Flow at IVP0111

$$\begin{aligned}\mathrm{SUCCESSLFIVP0111} \;=\; & \overline{\mathrm{DORMANT}}.\overline{\mathrm{P0103B}}.\overline{\mathrm{P0103PB}}.\overline{\mathrm{P0104B}}.\overline{\mathrm{P0104PB}}.\overline{\mathrm{P0105B}}.\overline{\mathrm{P0105PB}}.\overline{\mathrm{P0106B}} \\ & .\overline{\mathrm{P0106PB}}.\overline{\mathrm{P0113B}}.\overline{\mathrm{P0113PB}}.\overline{\mathrm{P0114B}}.\overline{\mathrm{P0114PB}}.\overline{\mathrm{IVP0110FC}}.\overline{\mathrm{IVP0110B}}.\overline{\mathrm{CT0110F}} \\ & .\overline{\mathrm{IVP0110S}}.\overline{\mathrm{IVP0110PB}}.\overline{\mathrm{BP0110B}}.\overline{\mathrm{BP0110PB}} \\ & +\overline{\mathrm{ACTIVE}}.\overline{\mathrm{PP0110FO}}\end{aligned}$$

D.2.10 Working Flow at IVP0121

SUCCESSHFIVP0121 = $\overline{\text{DORMANT}}.\overline{\text{P0107B}}.\overline{\text{P0107F}}.\overline{\text{P0107PB}}.\overline{\text{P0107L}}.\overline{\text{P0108B}}.\overline{\text{P0108F}}.\overline{\text{P0108PB}}$
$.\overline{\text{P0108L}}.\overline{\text{P0103F}}.\overline{\text{P0103L}}.\overline{\text{P0118B}}.\overline{\text{P0118F}}.\overline{\text{P0118PB}}.\overline{\text{P0118L}}.\overline{\text{P0119B}}.\overline{\text{P0119F}}$
$.\overline{\text{P0119PB}}.\overline{\text{P0119L}}.\overline{\text{P0120B}}.\overline{\text{P0120PB}}.\overline{\text{P0109B}}.\overline{\text{P0109PB}}.\overline{\text{P0110B}}.\overline{\text{P0110PB}}$
$.\overline{\text{P0111B}}.\overline{\text{P0111PB}}.\overline{\text{P0112B}}.\overline{\text{P0112PB}}.\overline{\text{IVP0120FO}}.\overline{\text{IVP0120S}}.\overline{\text{IVP0120L}}$
$.\overline{\text{PP0120FSO}}.\overline{\text{PP0120FM}}.\overline{\text{PP0120L}}.\overline{\text{PSV0120B}}.\overline{\text{PSV0120L}}.\overline{\text{PSV0120ISC}}$

D.2.11 Working Low Flow at IVP0121

SUCCESSLFIVP0121 = $\overline{\text{DORMANT}}.\overline{\text{P0109B}}.\overline{\text{P0109PB}}.\overline{\text{P0110B}}.\overline{\text{P0110PB}}.\overline{\text{P0111B}}.\overline{\text{P0111PB}}.\overline{\text{P0112B}}$
$.\overline{\text{P0112PB}}.\overline{\text{P0113B}}.\overline{\text{P0113PB}}.\overline{\text{P0114B}}.\overline{\text{P0114PB}}.\overline{\text{IVP0120FC}}.\overline{\text{IVP0120B}}.\overline{\text{CT0120F}}$
$.\overline{\text{IVP0120S}}.\overline{\text{IVP0120PB}}.\overline{\text{BP0120B}}.\overline{\text{BP0120PB}}$
$+\overline{\text{ACTIVE}}.\overline{\text{PP0120FO}}$

D.2.12 Working Decreasing Level at LT0110

DecLevelLT0110 = $\overline{\text{DORMANT}}.\overline{\text{TK0110R}}.\overline{\text{TK0110L}}.\overline{\text{P0121F}}.\overline{\text{P0121L}}.\overline{\text{IVP0130FO}}.\overline{\text{CT0130T}}.\overline{\text{IVP0130S}}$
$.\overline{\text{IVP0130L}}.\overline{\text{P0101F}}.\overline{\text{P0101L}}.\overline{\text{PP0110L}}.\overline{\text{P0107F}}.\overline{\text{P0107L}}.\overline{\text{PP0120L}}$

D.2.13 Working Constant Level at LT0110

ConstLevelLT0110 = $\overline{\text{DORMANT}}.\overline{\text{TK0110R}}.\overline{\text{TK0110L}}.\overline{\text{P0101F}}.\overline{\text{P0101L}}.\overline{\text{P0102F}}.\overline{\text{P0102L}}.\overline{\text{P0103F}}$
$.\overline{\text{P0103L}}.\overline{\text{P0115F}}.\overline{\text{P0115L}}.\overline{\text{P0116F}}.\overline{\text{P0116L}}.\overline{\text{PP0110L}}.\overline{\text{IVP0110L}}.\overline{\text{PSV0110L}}$
$.\overline{\text{P0107F}}.\overline{\text{P0107L}}.\overline{\text{P0108F}}.\overline{\text{P0108L}}.\overline{\text{P0109F}}.\overline{\text{P0109L}}.\overline{\text{P0118F}}.\overline{\text{P0118L}}.\overline{\text{P0119F}}$
$.\overline{\text{P0119L}}.\overline{\text{PP0120L}}.\overline{\text{IVP0120L}}.\overline{\text{PSV0120L}}.\overline{\text{P0121F}}.\overline{\text{P0121L}}.\overline{\text{IVP0130FO}}$
$.\overline{\text{CT0130T}}.\overline{\text{IVP0130S}}.\overline{\text{IVP0130L}}.\overline{\text{P0107F}}.\overline{\text{P0107L}}.\overline{\text{PP0120L}}.\overline{\text{IVP0110FO}}$
$.\overline{\text{IVP0120FO}}$
$+\overline{\text{ACTIVE}}.\overline{\text{TK0110R}}.\overline{\text{TK0110L}}.\overline{\text{P0101F}}.\overline{\text{P0101L}}.\overline{\text{P0102F}}.\overline{\text{P0102L}}.\overline{\text{P0103F}}$
$.\overline{\text{P0103L}}.\overline{\text{P0115F}}.\overline{\text{P0115L}}.\overline{\text{P0116F}}.\overline{\text{P0116L}}.\overline{\text{PP0110L}}.\overline{\text{IVP0110L}}.\overline{\text{PSV0110L}}$
$.\overline{\text{P0107F}}.\overline{\text{P0107L}}.\overline{\text{P0108F}}.\overline{\text{P0108L}}.\overline{\text{P0109F}}.\overline{\text{P0109L}}.\overline{\text{P0118F}}.\overline{\text{P0118L}}.\overline{\text{P0119F}}$
$.\overline{\text{P0119L}}.\overline{\text{PP0120L}}.\overline{\text{IVP0120L}}.\overline{\text{PSV0120L}}.\overline{\text{P0121F}}.\overline{\text{P0121L}}.\overline{\text{IVP0130FO}}$
$.\overline{\text{CT0130T}}.\overline{\text{IVP0130S}}.\overline{\text{IVP0130L}}.\overline{\text{P0107F}}.\overline{\text{P0107L}}.\overline{\text{PP0120L}}.\overline{\text{IVP0110FO}}$
$.\overline{\text{IVP0120FO}}.\overline{\text{PP0110FO}}.\overline{\text{PP0120FO}}$

Appendix E

ACTIVE Fuel Rig Results

E.1 Results for Both Lines

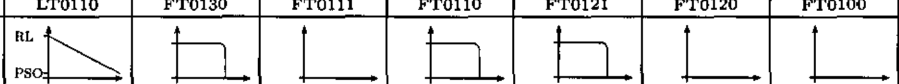
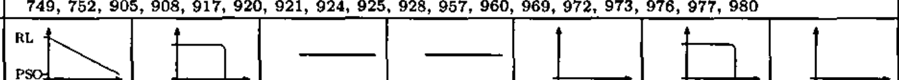
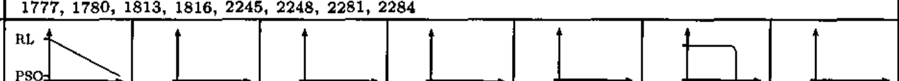
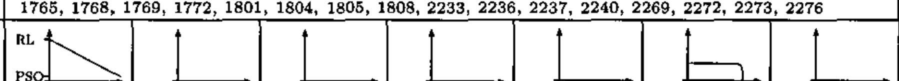
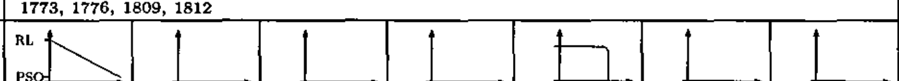
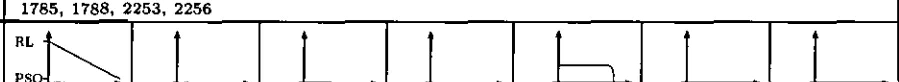
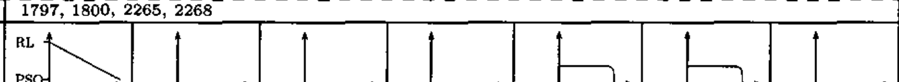
	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
-								-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
-								-	-	-
Scenarios	Dependent upon patterns on Line L1.									
1								27	27	27
Scenarios	1777, 1780, 1813, 1816, 2245, 2248, 2281, 2284									
2								18	18	18
Scenarios	1765, 1768, 1769, 1772, 1801, 1804, 1805, 1808, 2233, 2236, 2237, 2240, 2269, 2272, 2273, 2276									
3								126	126	126
Scenarios	1773, 1776, 1809, 1812									
4								24	24	30
Scenarios	1785, 1788, 2253, 2256									
5								360	360	471
Scenarios	1797, 1800, 2265, 2268									
6								102	102	102
Scenarios	1793, 1796, 2261, 2264									

Table E.1: Flow and level patterns for the main tank when there is a linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 1

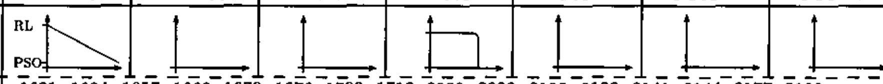
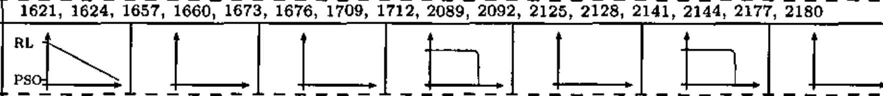
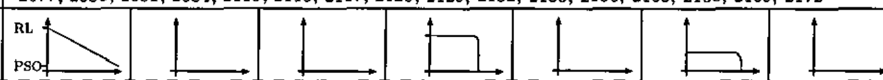
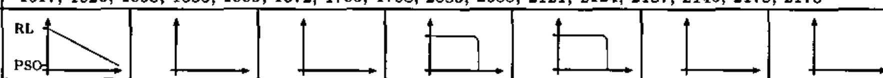
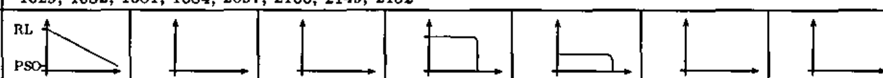
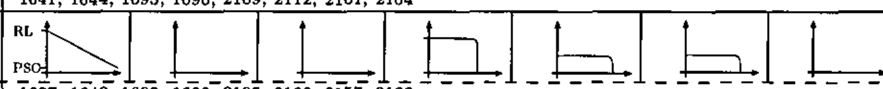
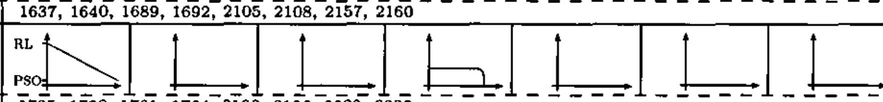
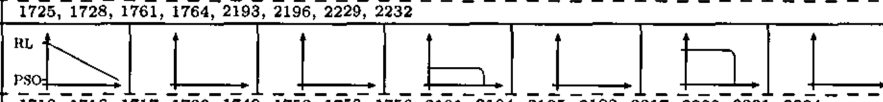
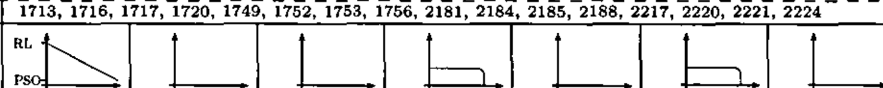
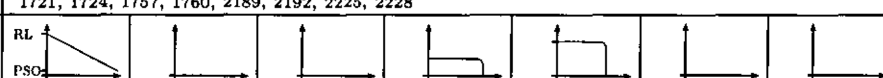
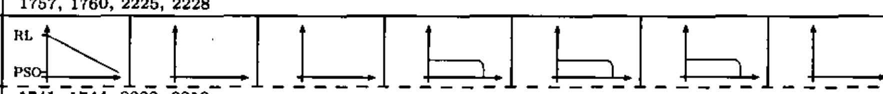
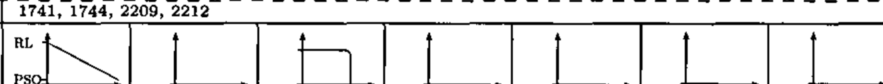
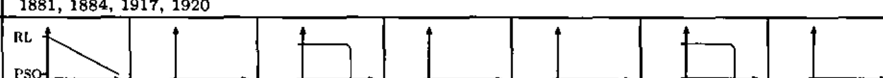
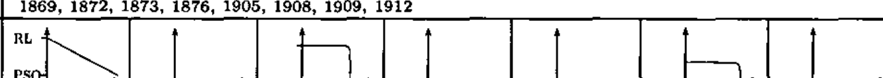
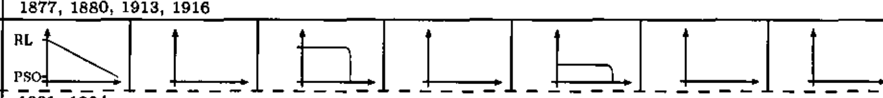
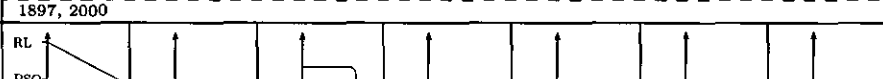
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
7								18	18	18
Scenarios	1621, 1624, 1657, 1660, 1673, 1676, 1709, 1712, 2089, 2092, 2125, 2128, 2141, 2144, 2177, 2180									
8								5	5	5
Scenarios	1609, 1612, 1613, 1616, 1645, 1648, 1649, 1652, 1661, 1664, 1665, 1668, 1697, 1700, 1701, 1704, 2077, 2080, 2081, 2084, 2113, 2116, 2117, 2120, 2129, 2132, 2133, 2136, 2165, 2168, 2169, 2172									
9								35	35	35
Scenarios	1617, 1620, 1653, 1656, 1669, 1672, 1705, 1708, 2085, 2088, 2121, 2124, 2137, 2140, 2173, 2176									
10								24	24	24
Scenarios	1629, 1632, 1681, 1684, 2097, 2100, 2149, 2152									
11								351	351	405
Scenarios	1641, 1644, 1693, 1696, 2109, 2112, 2161, 2164									
12								27	27	27
Scenarios	1637, 1640, 1689, 1692, 2105, 2108, 2157, 2160									
13								126	126	126
Scenarios	1725, 1728, 1761, 1764, 2193, 2196, 2229, 2232									
14								35	35	35
Scenarios	1713, 1716, 1717, 1720, 1749, 1752, 1753, 1756, 2181, 2184, 2185, 2188, 2217, 2220, 2221, 2224									
15								49	49	49
Scenarios	1721, 1724, 1757, 1760, 2189, 2192, 2225, 2228									
16								168	168	196
Scenarios	1757, 1760, 2225, 2228									
17								49	49	49
Scenarios	1741, 1744, 2209, 2212									
18								24	24	30
Scenarios	1881, 1884, 1917, 1920									
19								24	24	24
Scenarios	1869, 1872, 1873, 1876, 1905, 1908, 1909, 1912									
20								168	168	196
Scenarios	1877, 1880, 1913, 1916									
21								24	24	34
Scenarios	1901, 1904									
22								136	136	136
Scenarios	1897, 2000									
23								360	360	471
Scenarios	2037, 2040, 2073, 2076									

Table E.2: Flow and level patterns for the main tank when there is a linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
24	RL PSO							351	351	405
Scenarios	2025, 2028, 2029, 2032, 2061, 2064, 2065, 2068									
25	RL PSO							24	24	34
Scenarios	2045, 2048									
26	RL PSO							102	102	102
Scenarios	1985, 1988, 2009, 2012, 2013, 2016, 2021, 2024									
27	RL PSO							27	27	27
Scenarios	1973, 1976, 1977, 1980, 2009, 2012, 2013, 2016									
28	RL PSO							49	49	49
Scenarios	1981, 1984, 2017, 2020									
29	RL PSO							136	136	136
Scenarios	1993, 1996									
30	RL PSO							16	16	16
Scenarios	2001, 2004									
							Effectiveness Index I_E	0.933		

Table E.3: Flow and level patterns for the main tank when there is a linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL PSO							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
-	RL PSO							-	-	-
Scenarios	Dependent upon patterns on Line L1.									
1	RL							301	301	301
Scenarios	1777, 1780, 1813, 1816, 2245, 2248, 2281, 2284									
2	RL							98	98	98
Scenarios	1778, 1814, 2246, 2282									

Table E.4: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
3	RL							49	49	49
Scenarios	1779, 1815, 2247, 2283									
4	RL							120	120	120
Scenarios	1765, 1768, 1769, 1772, 1801, 1804, 1805, 1808, 2233, 2236, 2237, 2240, 2269, 2272, 2273, 2276									
5	RL							42	42	42
Scenarios	1766, 1770, 1802, 1806, 2234, 2238, 2270, 2274									
6	RL							21	21	21
Scenarios	1767, 1771, 1803, 1807, 2235, 2239, 2271, 2275									
7	RL							63	63	63
Scenarios	1773, 1776, 1809, 1812									
8	RL							320	320	380
Scenarios	1785, 1788, 2253, 2256									
9	RL							112	112	140
Scenarios	1786, 2254									
10	RL							56	56	70
Scenarios	1787, 2255									
11	RL							229	229	267
Scenarios	1797, 1800, 2265, 2268									
12	RL							17	17	17
Scenarios	1793, 1796, 2261, 2264									
13	RL							120	120	120
Scenarios	1621, 1624, 1657, 1660, 1673, 1676, 1709, 1712, 2089, 2092, 2125, 2128, 2141, 2144, 2177, 2180									
14	RL							42	42	42
Scenarios	1622, 1658, 1674, 1710, 2090, 2126, 2142, 2178									
15	RL							21	21	21
Scenarios	1623, 1659, 1675, 1711, 2091, 2127, 2143, 2179									
16	RL							25	25	25
Scenarios	1609, 1612, 1613, 1616, 1645, 1648, 1649, 1652, 1661, 1664, 1665, 1668, 1697, 1700, 1701, 1704, 2077, 2080, 2081, 2084, 2113, 2116, 2117, 2120, 2129, 2132, 2133, 2136, 2165, 2168, 2169, 2172									
17	RL							10	10	10
Scenarios	1610, 1614, 1646, 1650, 1662, 1666, 1698, 1702, 2078, 2082, 2114, 2118, 2130, 2134, 2166, 2170									
18	RL							55	55	55
Scenarios	1611, 1647, 1651, 1663, 1667, 1699, 1703, 2079, 2083, 2115, 2119, 2131, 2135, 2167, 2171									
19	RL							45	45	45
Scenarios	1617, 1620, 1653, 1656, 1669, 1672, 1705, 1708, 2085, 2088, 2121, 2124, 2137, 2140, 2173, 2176									

Table E.5: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
20	RL							18	18	18
Scenarios	1618, 1654, 1670, 1706, 2086, 2122, 2138, 2174									
21	RL							9	9	9
Scenarios	1619, 1655, 1671, 1707, 2087, 2123, 2139, 2175									
22	RL							120	120	120
Scenarios	1629, 1632, 1681, 1684, 2097, 2100, 2149, 2152									
23	RL							48	48	48
Scenarios	1630, 1682, 2098, 2150									
24	RL							24	24	24
Scenarios	1631, 1683, 2099, 2151									
25	RL							48	48	56
Scenarios	1641, 1644, 1693, 1696, 2109, 2112, 2161, 2164									
26	RL							28	28	28
Scenarios	1637, 1640, 1689, 6192, 2105, 2108, 2157, 2160									
27	RL							8	8	8
Scenarios	1638, 1690, 2106, 2158									
28	RL							4	4	4
Scenarios	1639, 1691, 2107, 2159									
29	RL							63	63	63
Scenarios	1725, 1728, 1761, 1764, 2193, 2196, 2229, 2232									
30	RL							45	45	45
Scenarios	1713, 1716, 1717, 1720, 1749, 1752, 1753, 1756, 2181, 2184, 2185, 2188, 2217, 2220, 2221, 2224									
31	RL							18	18	18
Scenarios	1714, 1718, 1750, 1754, 2182, 2186, 2218, 2222									
32	RL							9	9	9
Scenarios	1715, 1719, 1751, 1755, 2183, 2187, 2219, 2223									
33	RL							32	32	32
Scenarios	1721, 1724, 1757, 1760, 2189, 2192, 2225, 2228									
34	RL							48	48	48
Scenarios	1757, 1760, 2225, 2228									
35	RL							14	14	14
Scenarios	1741, 1744, 2209, 2212									
36	RL							320	320	380
Scenarios	1881, 1884, 1917, 1920									

Table E.6: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
37	RL							112	12	140
Scenarios	1882, 1918									
38	RL							56	56	70
Scenarios	1883, 1919									
39	RL							120	120	120
Scenarios	1869, 1872, 1873, 1876, 1905, 1908, 1909, 1912									
40	RL							48	48	48
Scenarios	1870, 1874, 1906, 1910									
41	RL							24	24	24
Scenarios	1871, 1875, 1907, 1911									
42	RL							48	48	48
Scenarios	1641, 1644, 1693, 1696, 2109, 2112, 2161, 2164									
43	RL							330	330	330
Scenarios	1889, 1892									
44	RL							132	132	132
Scenarios	1890									
45	RL							726	726	726
Scenarios	1891									
46	RL							317	317	317
Scenarios	1901, 1904									
47	RL							82	82	82
Scenarios	1902									
48	RL							41	41	41
Scenarios	1903									
49	RL							229	229	267
Scenarios	2037, 2040, 2073, 2076									
50	RL							48	48	56
Scenarios	2025, 2028, 2029, 2032, 2061, 2064, 2065, 2068									
51	RL							317	317	317
Scenarios	2045, 2048									
52	RL							82	82	82
Scenarios	2046									
53	RL							41	41	41
Scenarios	2047									

Table E.7: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 4

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
54	RL							161	161	161
Scenarios	2057, 2060									
55	RL							2	2	2
Scenarios	2058									
56	RL							1	1	1
Scenarios	2059									
57	RL							17	17	17
Scenarios	1985, 1988, 2021, 2024									
58	RL							28	28	28
Scenarios	1973, 1976, 1977, 1980									
59	RL							8	8	8
Scenarios	1974, 1978									
60	RL							4	4	4
Scenarios	1975, 1979									
61	RL							14	14	14
Scenarios	1981, 1984, 2017, 2020									
							Effectiveness Index I_E	0.972		

Table E.8: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode - Table 5

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 157, 160, 169, 172, 173, 176, 177, 180, 209, 212, 221, 224, 225, 228, 229, 232, 261, 264, 273, 276, 277, 280, 281, 284, 1609, 1612, 1621, 1624, 1625, 1628, 1629, 1632, 1765, 1768, 1777, 1780, 1781, 1784, 1785, 1788, 1817, 1820, 1829, 1832, 1833, 1836, 1837, 1840, 1869, 1872, 1881, 1884, 1885, 1888, 1889, 1892									
1	RL PSO							24	24	24
Scenarios	945, 948, 1037, 1040									
2	RL PSO							24	24	24
Scenarios	993, 996, 1005, 1008									

Table E.9: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
3	RL PSO							4	4	4
Scenarios	997, 1000									
4	RL PSO							40	40	40
Scenarios	1001, 1004									
5	RL PSO							2	2	2
Scenarios	957, 960, 969, 972, 973, 976, 977, 980									
6	RL PSO							28	28	28
Scenarios	981, 984, 989, 992									
7	RL PSO							24	24	24
Scenarios	985, 988									
8	RL PSO							40	40	40
Scenarios	1021, 1024									
9	RL PSO							2	2	2
Scenarios	717, 720, 821, 824, 837, 840, 853, 856									
10	RL PSO							28	28	28
Scenarios	869, 87, 901, 904									
11	RL PSO							24	24	24
Scenarios	885, 888									
							Effectiveness Index I_E	1.000		

Table E.10: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 157, 160, 169, 172, 173, 176, 177, 180, 209, 212, 221, 224, 225, 228, 229, 232, 261, 264, 273, 276, 277, 280, 281, 284, 1609, 1612, 1621, 1624, 1625, 1628, 1629, 1632, 1765, 1768, 1777, 1780, 1781, 1784, 1785, 1788, 1817, 1820, 1829, 1832, 1833, 1836, 1837, 1840, 1869, 1872, 1881, 1884, 1885, 1888, 1889, 1892									
1	RL							164	164	164
Scenarios	945, 948, 1037, 1040									
2	RL							52	52	52
Scenarios	946, 1038									

Table E.11: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
3	RL							26	26	26
Scenarios	947, 1038									
4	RL							164	164	164
Scenarios	945, 948, 1037, 1040									
5	RL							52	52	52
Scenarios	994, 1006									
6	RL							26	26	26
Scenarios	995, 1007									
7	RL							20	20	20
Scenarios	997, 1000									
8	RL							8	8	8
Scenarios	998									
9	RL							4	4	4
Scenarios	999									
10	RL							8	8	8
Scenarios	1001, 1004									
11	RL							10	10	10
Scenarios	957, 960, 969, 972, 973, 976, 977, 980									
12	RL							4	4	4
Scenarios	958, 970, 974, 978									
13	RL							22	22	22
Scenarios	959, 971, 975, 979									
14	RL							144	144	144
Scenarios	981, 984, 989, 992									
15	RL							64	64	64
Scenarios	982, 990									
16	RL							32	32	32
Scenarios	983, 991									
17	RL							14	14	14
Scenarios	985, 988									
18	RL							4	4	4
Scenarios	986									
19	RL							2	2	2
Scenarios	987									

Table E.12: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
20	RL							8	8	8
Scenarios	1021, 1024									
21	RL							10	10	10
Scenarios	717, 720, 821, 824, 837, 840, 853, 856									
22	RL							4	4	4
Scenarios	718, 822, 838, 854									
23	RL							22	22	22
Scenarios	719, 823, 839, 855									
24	RL							144	144	144
Scenarios	869, 872, 901, 904									
25	RL							64	64	64
Scenarios	870, 902									
26	RL							32	32	32
Scenarios	871, 903									
27	RL							14	14	14
Scenarios	885, 888									
28	RL							4	4	4
Scenarios	886									
29	RL							2	2	2
Scenarios	887									
							Effectiveness Index I_E	1.000		

Table E.13: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL PSO							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									

Table E.14: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
-	RL PSO		—	—				-	-	-
Scenarios	Dependent upon patterns on Line L1.									
1	RL PSO							24	24	24
Scenarios	1217, 1220, 1221, 1224, 1233, 1236, 1237, 1240, 1597, 1600, 1601, 1604, 1617, 1620, 1621, 1624									
2	RL PSO							42	42	42
Scenarios	1225, 1228, 1241, 1244, 1605, 1608, 1625, 1628									
3	RL PSO							42	42	54
Scenarios	1229, 1232, 1613, 1616									
4	RL PSO							24	24	24
Scenarios	1073, 1076, 1109, 1112, 1125, 1128, 1161, 1164, 1453, 1456, 1489, 1492, 1505, 1508, 1541, 1544									
5	RL PSO							22	22	22
Scenarios	1061, 1064, 1065, 1068, 1097, 1100, 1101, 1104, 1113, 1116, 1117, 1120, 1149, 1152, 1153, 1156, 1441, 1444, 1445, 1448, 1477, 1480, 1481, 1484, 1493, 1496, 1497, 1500, 1529, 1532, 1533, 1536									
6	RL PSO							42	42	42
Scenarios	1069, 1072, 1105, 1108, 1121, 1124, 1157, 1160, 1449, 1452, 1485, 1488, 1501, 1504, 1537, 1540									
7	RL PSO							32	32	32
Scenarios	1081, 1084, 1133, 1136, 1461, 1464, 1513, 1516									
8	RL PSO							468	468	468
Scenarios	1093, 1096, 1145, 1148, 1473, 1476, 1525, 1528									
9	RL PSO							42	42	46
Scenarios	1089, 1092, 1141, 1144, 1469, 1472, 1521, 1524									
10	RL PSO							42	42	42
Scenarios	1177, 1180, 1213, 1216, 1557, 1560, 1593, 1596									
11	RL PSO							42	42	42
Scenarios	1165, 1168, 1169, 1172, 1201, 1204, 1205, 1208, 1545, 1548, 1549, 1552, 1581, 1584, 1585, 1588									
12	RL PSO							49	49	49
Scenarios	1173, 1176, 1209, 1212, 1553, 1556, 1589, 1592									
13	RL PSO							56	56	56
Scenarios	1185, 1188, 1565, 1568									
14	RL PSO							819	819	819
Scenarios	1197, 1200, 1577, 1580									
16	RL PSO							32	32	32
Scenarios	1281, 1284, 1297, 1300									

Table E.15: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
17	RL PSO							56	56	56
Scenarios	1285, 1288, 1301, 1304									
18	RL PSO							72	72	72
Scenarios	1289, 1292									
19	RL PSO							468	468	468
Scenarios	1409, 1412, 1413, 1416, 1429, 1432, 1433, 1436									
20	RL PSO							819	819	819
Scenarios	1417, 1420, 1437, 1440									
21	RL PSO							1053	1053	1053
Scenarios	1425, 1428									
22	RL PSO							42	42	54
Scenarios	1369, 1372, 1405, 1408									
23	RL PSO							42	42	46
Scenarios	1357, 1360, 1361, 1364, 1393, 1396, 1397, 1400									
24	RL PSO							49	49	49
Scenarios	1365, 1368, 1401, 1404									
25	RL PSO							72	72	72
Scenarios	1377, 1380									
26	RL PSO							1053	1053	1053
Scenarios	1389, 1392									
27	RL PSO							49	49	49
Scenarios	1385, 1388									
							Effectiveness Index I_E	0.977		

Table E.16: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 3

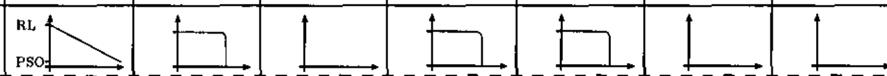
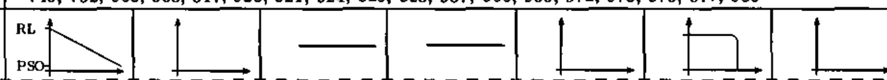
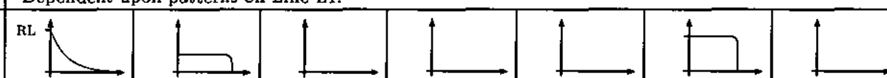
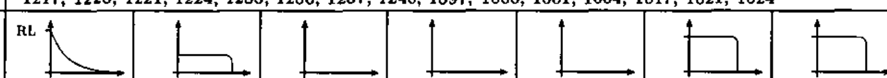
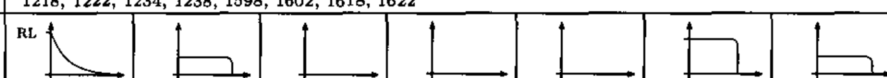
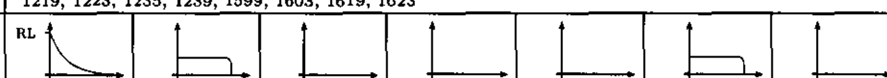
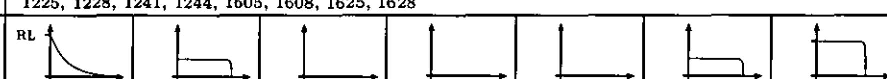
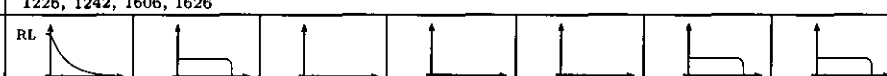
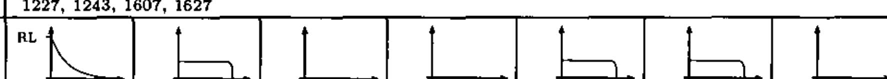
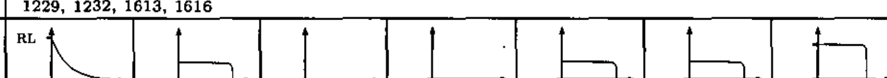
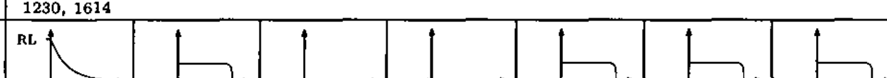
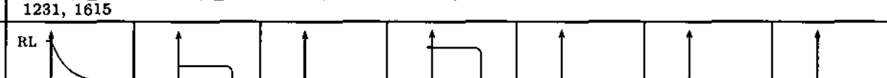
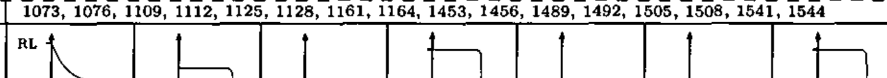
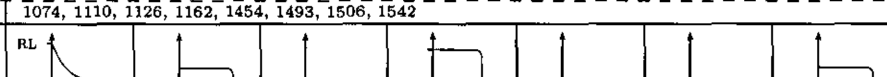
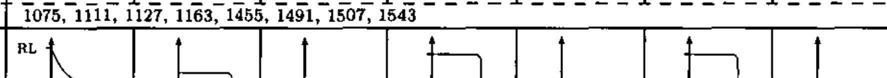
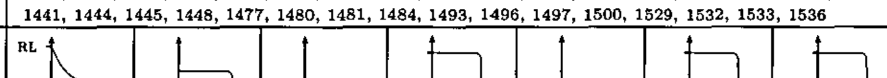
	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
-								-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 53, 56, 65, 68, 69, 72, 73, 76, 469, 472, 481, 484, 485, 488, 489, 492, 521, 524, 533, 536, 537, 540, 541, 544, 677, 680, 689, 692, 693, 696, 697, 700, 729, 732, 741, 744, 745, 748, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
-								-	-	-
Scenarios	Dependent upon patterns on Line L1.									
1								160	160	160
Scenarios	1217, 1220, 1221, 1224, 1233, 1236, 1237, 1240, 1597, 1600, 1601, 1604, 1617, 1621, 1624									
2								56	56	56
Scenarios	1218, 1222, 1234, 1238, 1598, 1602, 1618, 1622									
3								28	28	28
Scenarios	1219, 1223, 1235, 1239, 1599, 1603, 1619, 1623									
4								294	294	294
Scenarios	1225, 1228, 1241, 1244, 1605, 1608, 1625, 1628									
5								126	126	126
Scenarios	1226, 1242, 1606, 1626									
6								693	693	693
Scenarios	1227, 1243, 1607, 1627									
7								364	364	468
Scenarios	1229, 1232, 1613, 1616									
8								98	98	126
Scenarios	1230, 1614									
9								49	49	63
Scenarios	1231, 1615									
10								160	160	160
Scenarios	1073, 1076, 1109, 1112, 1125, 1128, 1161, 1164, 1453, 1456, 1489, 1492, 1505, 1508, 1541, 1544									
11								56	56	56
Scenarios	1074, 1110, 1126, 1162, 1454, 1493, 1506, 1542									
12								28	28	28
Scenarios	1075, 1111, 1127, 1163, 1455, 1491, 1507, 1543									
13								110	110	110
Scenarios	1061, 1064, 1065, 1068, 1097, 1100, 1101, 1104, 1113, 1116, 1117, 1120, 1149, 1152, 1153, 1156, 1441, 1444, 1445, 1448, 1477, 1480, 1481, 1484, 1493, 1496, 1497, 1500, 1529, 1532, 1533, 1536									
14								44	44	44
Scenarios	1062, 1066, 1098, 1102, 1114, 1118, 1150, 1154, 1442, 1446, 1478, 1482, 1494, 1498, 1530, 1534									

Table E.17: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

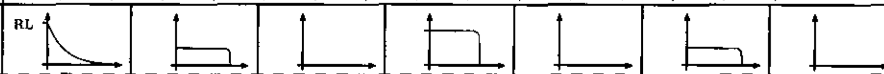
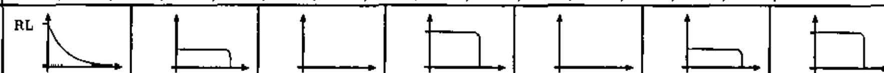
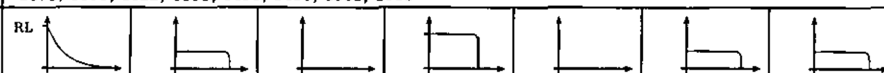
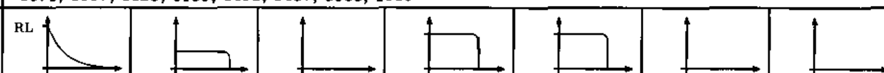
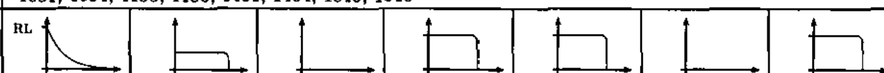
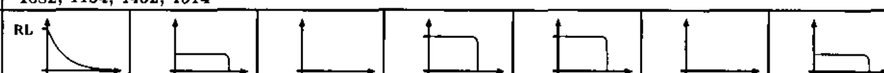
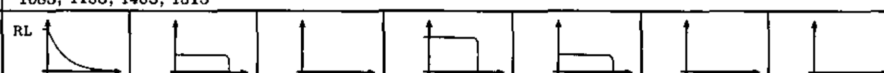
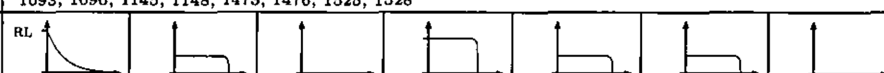
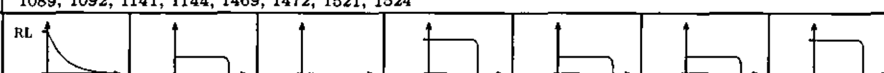
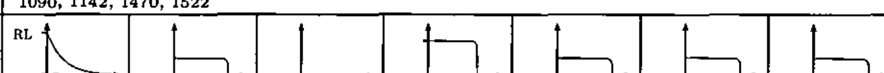
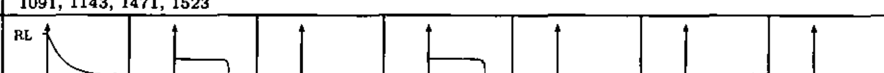
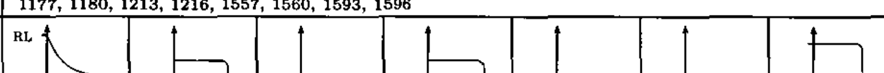
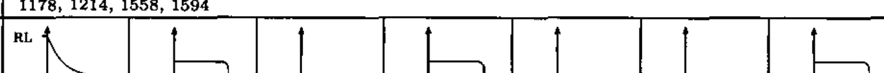
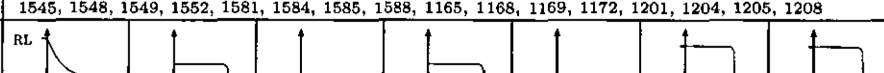
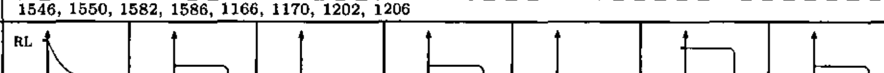
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
15								32	32	32
Scenarios	1063, 1067, 1099, 1103, 1115, 1119, 1151, 1155, 1443, 1445, 1479, 1483, 1495, 1499, 1531, 1535									
16								222	222	222
Scenarios	1069, 1072, 1105, 1108, 1121, 1124, 1157, 1160, 1449, 1452, 1485, 1488, 1501, 1504, 1537, 1540									
17								108	108	108
Scenarios	1070, 1106, 1122, 1158, 1450, 1486, 1502, 1538									
18								54	54	54
Scenarios	1071, 1107, 1123, 1159, 1451, 1487, 1503, 1539									
19								160	160	160
Scenarios	1081, 1084, 1133, 1136, 1461, 1464, 1513, 1516									
20								64	64	64
Scenarios	1082, 1134, 1462, 1514									
21								352	352	352
Scenarios	1083, 1135, 1463, 1515									
22								64	64	64
Scenarios	1093, 1096, 1145, 1148, 1473, 1476, 1525, 1528									
23								294	294	322
Scenarios	1089, 1092, 1141, 1144, 1469, 1472, 1521, 1524									
24								84	84	92
Scenarios	1090, 1142, 1470, 1522									
25								42	42	46
Scenarios	1091, 1143, 1471, 1523									
26								294	294	294
Scenarios	1177, 1180, 1213, 1216, 1557, 1560, 1593, 1596									
27								126	126	126
Scenarios	1178, 1214, 1558, 1594									
28								693	693	693
Scenarios	1179, 1215, 1559, 1595									
29								222	222	222
Scenarios	1545, 1548, 1549, 1552, 1581, 1584, 1585, 1588, 1165, 1168, 1169, 1172, 1201, 1204, 1205, 1208									
30								108	108	108
Scenarios	1546, 1550, 1582, 1586, 1166, 1170, 1202, 1206									
31								541	54	54
Scenarios	1547, 1551, 1583, 1587, 1167, 1171, 1203, 1207									

Table E.18: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
32	RL							277	277	277
Scenarios	1173, 1176, 1209, 1212, 1553, 1556, 1589, 1592									
33	RL							162	162	162
Scenarios	1176, 1210, 1554, 1590									
34	RL							81	81	81
Scenarios	1175, 1211, 1555, 1591									
35	RL							296	296	296
Scenarios	1565, 1568, 1185, 1188									
36	RL							144	144	144
Scenarios	1566, 1186									
37	RL							72	72	72
Scenarios	1567, 1187									
38	RL							160	160	160
Scenarios	1281, 1284, 1297, 1300									
39	RL							64	64	64
Scenarios	1282, 1298									
40	RL							352	352	352
Scenarios	1283, 1299									
41	RL							296	296	296
Scenarios	1285, 1288, 1301, 1304									
42	RL							144	144	144
Scenarios	1286, 1302									
43	RL							72	72	72
Scenarios	1287, 1303									
44	RL							504	504	504
Scenarios	1289, 1292									
45	RL							144	144	144
Scenarios	1290									
46	RL							72	72	72
Scenarios	1291									
47	RL							64	64	64
Scenarios	1409, 1412, 1413, 1416, 1429, 1432, 1433, 1436									
48	RL							364	364	468
Scenarios	1369, 1372, 1405, 1408									

Table E.19: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
49	RL							98	98	126
Scenarios	1370, 1406									
50	RL							49	49	63
Scenarios	1371, 1407									
51	RL							294	294	322
Scenarios	1357, 1360, 1361, 1364, 1393, 1396, 1397, 1400									
52	RL							84	84	92
Scenarios	1358, 1362, 1394, 1398									
53	RL							42	42	46
Scenarios	1359, 1363, 1395, 1399									
54	RL							504	504	504
Scenarios	1377, 1380									
55	RL							144	144	144
Scenarios	1378									
56	RL							792	792	792
Scenarios	1379									
							Effectiveness Index I_E	0.967		

Table E.20: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 4

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 157, 160, 169, 172, 173, 176, 177, 180, 209, 212, 221, 224, 225, 228, 229, 232, 261, 264, 273, 276, 277, 280, 281, 284, 1609, 1612, 1621, 1624, 1625, 1628, 1629, 1632, 1765, 1768, 1777, 1780, 1781, 1784, 1785, 1788, 1817, 1820, 1829, 1832, 1833, 1836, 1837, 1840, 1869, 1872, 1881, 1884, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
1	RL PSO							96	96	96
Scenarios	1481, 1484, 1621, 1624									
2	RL PSO							240	240	240
Scenarios	1485, 1488, 1625, 1628									

Table E.21: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
3	RL / PSO							192	192	192
Scenarios	1469, 1472, 1613, 1616									
4	RL / PSO							96	96	96
Scenarios	1529, 1533, 1541, 1544									
5	RL / PSO							4	4	4
Scenarios	1533, 1536									
6	RL / PSO							8	8	8
Scenarios	1493, 1496, 1505, 1508, 1509, 1512, 1513, 1516									
7	RL / PSO							112	112	112
Scenarios	1517, 1520, 1525, 1528									
8	RL / PSO							12	12	12
Scenarios	1521, 1524									
9	RL / PSO							240	240	240
Scenarios	1581, 1584, 1593, 1596									
10	RL / PSO							125	125	125
Scenarios	1545, 1548, 1557, 1560, 1561, 1564, 1565, 1568									
11	RL / PSO							280	280	280
Scenarios	1568, 1572, 1577, 1580									
12	RL / PSO							7	7	7
Scenarios	1573, 1576									
13	RL / PSO							8	8	8
Scenarios	1101, 1104, 1237, 1240, 1269, 1272, 1297, 1300									
14	RL / PSO							125	125	125
Scenarios	1105, 1108, 1241, 1244, 1273, 1276									
15	RL / PSO							16	16	16
Scenarios	1089, 1092, 1229, 1232, 1261, 1264, 1289, 1292									
16	RL / PSO							112	112	112
Scenarios	1345, 1348, 1433, 1436									
17	RL / PSO							280	280	280
Scenarios	1349, 1352, 1437, 1440									
18	RL / PSO							224	224	224
Scenarios	1335, 1427									

Table E.22: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
19	RL PSO							192	192	192
Scenarios	1393, 1396, 1405, 1408									
20	RL PSO							12	12	12
Scenarios	1397, 1400									
21	RL PSO							7	7	7
Scenarios	1401, 1404									
22	RL PSO							16	16	16
Scenarios	1357, 1360, 1369, 1372, 1373, 1376, 1377, 1380									
23	RL PSO							224	224	224
Scenarios	1381, 1384, 1389, 1392									
24	RL PSO							49	49	49
Scenarios	1385, 1388									
							Effectiveness Index I_E	1.000		

Table E.23: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 17, 20, 21, 24, 157, 160, 169, 172, 173, 176, 177, 180, 209, 212, 221, 224, 225, 228, 229, 232, 261, 264, 273, 276, 277, 280, 281, 284, 1609, 1612, 1621, 1624, 1625, 1628, 1629, 1632, 1765, 1768, 1777, 1780, 1781, 1784, 1785, 1788, 1817, 1820, 1829, 1832, 1833, 1836, 1837, 1840, 1869, 1872, 1881, 1884, 749, 752, 905, 908, 917, 920, 921, 924, 925, 928, 957, 960, 969, 972, 973, 976, 977, 980									
1	RL							8	8	8
Scenarios	1481, 1484, 1621, 1624									
3	RL							7	7	7
Scenarios	1485, 1488, 1625, 1628									
4	RL							121	121	121
Scenarios	1469, 1472, 1613m 1616									
5	RL							26	26	26
Scenarios	1470, 1614									

Table E.24: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
6								13	13	13
Scenarios	1471, 1615									
7								8	8	8
Scenarios	1529, 1532, 1541, 1544									
8								8	8	8
Scenarios	1537, 1540									
9								40	40	40
Scenarios	1493, 1496, 1505, 1508, 1509, 1512, 1513, 1516									
10								16	16	16
Scenarios	1494, 1506, 1510, 1514									
11								8	8	8
Scenarios	1495, 1507, 1511, 1515									
12								16	16	16
Scenarios	1517, 1520, 1525, 1528									
13								7	7	7
Scenarios	1581, 1584, 1593, 1596									
14								8	8	8
Scenarios	1585, 1588									
15								-	-	-
Scenarios	1586									
16								118	118	118
Scenarios	1545, 1548, 1557, 1560, 1561, 1564, 565, 1568									
17								48	48	48
Scenarios	1546, 1558, 1561, 1565									
18								24	24	24
Scenarios	1547, 1559, 1562, 1566									
19								104	140	104
Scenarios	1569, 1572, 1577, 1580									
20								4	4	4
Scenarios	1573, 1576									
21								40	40	40
Scenarios	1101, 1104, 1237, 1240, 1269, 1272, 1297, 1300									

Table E.25: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
22	RL							16	16	16
Scenarios	1102, 1238, 1270, 1298									
23	RL							8	8	8
Scenarios	1103, 1239, 1271, 1299									
24	RL							118	118	118
Scenarios	1105, 1108, 1241, 1244, 1273, 1276, 1301, 1304									
25	RL							48	48	48
Scenarios	1106, 1242, 1274, 1302									
26	RL							24	24	24
Scenarios	1107, 1243, 1275, 1303									
27	RL							112	112	112
Scenarios	1089, 1092, 1229, 1232, 1261, 1264, 1289, 1292									
28	RL							32	32	32
Scenarios	1090, 1230, 1262, 1290									
29	RL							22	22	22
Scenarios	1091, 1231, 1263, 1291									
30	RL							16	16	16
Scenarios	1345, 1348									
31	RL							104	104	104
Scenarios	1349, 1352									
32	RL							130	130	130
Scenarios	1333, 1336, 1425, 1428									
33	RL							32	32	32
Scenarios	1334, 1426									
34	RL							16	16	16
Scenarios	1335, 1427									
35	RL							121	121	121
Scenarios	1393, 1396, 1405, 1408									
36	RL							26	26	26
Scenarios	1394, 1406									
37	RL							13	13	13
Scenarios	1395, 1407									

Table E.26: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 3

	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	RECYCLE L2	STREAM FLOW L2	DRAIN FLOW	Results		Number of Actual Possibilities
	LT0110	FT0130	FT0111	FT0110	FT0121	FT0120	FT0100	n_i	nc_i	na_i
38	RL							4	4	4
Scenarios	1401, 1404									
39	RL							112	112	112
Scenarios	1357, 1360 1369, 1372, 1373, 1376, 1377, 1380									
40	RL							32	32	32
Scenarios	1358, 1370, 1374, 1378									
41	RL							22	22	22
Scenarios	1359, 1371, 1375, 1379									
42	RL							130	130	130
Scenarios	1381, 1384, 1389, 1392									
43	RL							32	32	32
Scenarios	1382, 1390									
44	RL							16	16	16
Scenarios	1383, 1391									
45	RL							9	9	9
Scenarios	1385, 1388									
46	RL							2	2	2
Scenarios	1386									
47	RL							1	1	1
Scenarios	1387									
							Effectiveness Index I_E	1.000		

Table E.27: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 4

E.2 Results for an Individual Line

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196	RL PSO					-	-	-
1	165, 168, 201, 204	RL					53	53	53
2	173, 176	RL					10	10	10
3	185, 188	RL					80	80	80
						Effectiveness Index I_E	1.000		

Table E.28: Flow and level patterns for the main tank when there is a constant level and no flow out of the tank in the ACTIVE operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196	RL PSO					-	-	-
1	153, 156, 157, 160, 189, 192, 193, 196	RL PSO					3	3	3
2	181, 184	RL PSO					17	17	17
3	161, 164, 197, 200	RL PSO					21	21	21
4	165, 168, 201, 204	RL PSO					6	3	3
5	173, 176	RL PSO					8	0	16
6	185, 188	RL PSO					117	53	53
						Effectiveness Index I_E	0.659		

Table E.29: Flow and level patterns for the main tank when there is a linearly decreasing level and no flow out of the tank in the ACTIVE operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196	RL PSO					-	-	-
1	165, 168, 201, 204	RL					58	58	58
2	166, 202	RL					14	14	14
3	167, 203	RL					77	77	77
4	153, 156, 157, 160, 189, 192, 193, 196	RL					24	24	24
5	154, 158, 190, 194	RL					6	6	6
6	155, 159, 191, 195	RL					33	33	33
7	161, 164, 197, 200	RL					174	174	174
8	162, 198	RL					54	54	54
9	163, 199	RL					297	297	297
10	173, 176	RL					80	80	80
11	174	RL					20	20	20
12	175	RL					110	110	110
13	185, 188	RL					1258	1258	1258
14	186	RL					348	348	348
15	187	RL					1914	1914	1914
16	181, 184	RL					170	170	170
17	182	RL					34	34	34
18	183	RL					187	187	187
						Effectiveness Index I_E	1.000		

Table E.30: Flow and level patterns for the main tank when there is a non-linearly decreasing level and no flow out of the tank in the ACTIVE operating mode

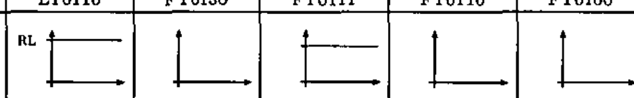
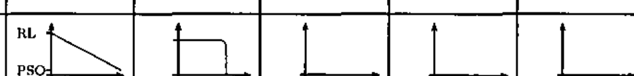
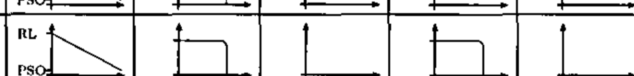
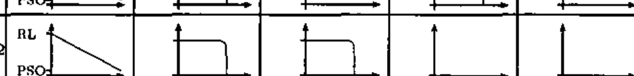
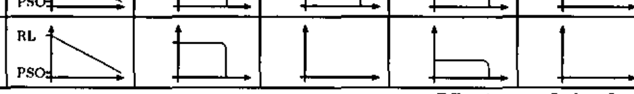
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 13, 16, 33, 36, 37, 40, 153, 156, 165, 168, 169, 172, 173, 176						-	-	-
1	85, 88, 97, 100						24	24	24
2	89, 92						2	2	2
3	49, 52, 61, 64, 65, 68, 69, 72						36	36	36
4	73, 76, 81, 84						2	2	2
5	77, 80						28	28	28
6	57, 60, 93, 96						24	24	24
						Effectiveness Index I_E	1.000		

Table E.31: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the ACTIVE operating mode

	Scenarios	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	DRAIN FLOW	Results		Number of Actual Possibilities
		LT0110	FT0130	FT0111	FT0110	FT0100	n_i	nc_i	na_i
-	1, 4, 13, 16, 33, 36, 37, 40, 153, 156, 165, 168, 169, 172, 173, 176	RL					-	-	-
1	85, 88, 97, 100	RL					164	164	164
2	86, 98	RL					52	52	52
3	87, 99	RL					286	286	286
4	89, 92	RL					16	16	16
5	90	RL					4	4	4
6	91	RL					22	22	22
7	57, 60, 93, 96	RL					36	36	36
8	49, 52, 61, 64, 65, 68, 69, 72	RL					10	10	10

Table E.32: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 1

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
9	50, 62, 66, 70	RL					4	4	4
10	51, 63, 67, 71	RL					22	22	22
11	73, 76, 81, 84	RL					144	144	144
12	74, 82	RL					64	64	64
13	75, 83	RL					352	352	352
14	77, 80	RL					168	168	168
15	78	RL					48	48	48
16	79	RL					264	264	264
						Effectiveness Index I_E	1.000		

Table E.33: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the ACTIVE operating mode - Table 2

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196	RL PSO					-	-	-
1	101, 104, 105, 108, 137, 140, 141, 144	RL PSO					4	4	4
2	109, 112, 145, 148	RL PSO					7	7	7
3	129, 132	RL PSO					9	9	9
4	121, 124	RL PSO					24	0	296
5	133, 136	RL PSO					351	0	117
6	113, 116, 149, 152	RL PSO					6	0	222
						Effectiveness Index I_E	0.500		

Table E.34: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
-	1, 4, 5, 8 33, 36, 37, 40 153, 156, 157, 160 189, 192, 193, 196	RL PSO					-	-	-
1	101, 104, 105, 108, 137, 140, 141, 144	RL					32	32	32
2	102, 106, 138, 142	RL					8	8	8
3	103, 107, 139, 143	RL					44	44	44
4	109, 112, 145, 148	RL					58	58	58
5	110, 146	RL					18	18	18
6	111, 147	RL					99	99	99
7	129, 132	RL					90	90	90
8	130	RL					18	18	18
9	131	RL					99	99	99
10	113, 116, 149, 152	RL					58	0	43
11	121, 124	RL					216	0	36
						Effectiveness Index I_E	0.818		

Table E.35: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
-	1, 4, 13, 16, 33, 36, 37, 40, 153, 156, 165, 168, 169, 172, 173, 176	RL					-	-	-
1	137, 140, 149, 152	RL PSO					444	444	444
2	101, 104, 113, 116, 117, 120, 121, 124	RL PSO					37	37	37

Table E.36: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

	Scenarios	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	DRAIN FLOW	Results		Number of Actual Possibilities
		LT0110	FT0130	FT0111	FT0110	FT0100	n_i	nc_i	na_i
3	125, 128, 133, 136	RL PSO					518	518	518
4	141, 144	RL PSO					132	132	132
5	145, 148	RL PSO					125	125	125
6	129, 132	RL PSO					16	16	16
					Effectiveness Index I_E		1.000		

Table E.37: Flow and level patterns for the main tank when there is a linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

	Scenarios	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	DRAIN FLOW	Results		Number of Actual Possibilities
		LT0110	FT0130	FT0111	FT0110	FT0100	n_i	nc_i	na_i
-	1, 4, 13, 16, 33, 36, 37, 40, 153, 156, 165, 168, 169, 172, 173, 176	RL					-	-	-
1	137, 140, 149, 152	RL					158	158	158
2	138, 150	RL					26	26	26
3	139, 151	RL					13	13	13
4	101, 104, 113, 116 117, 120, 121, 124	RL					191	191	191
5	102, 114, 118, 122	RL					82	82	82
6	103, 115, 119, 123	RL					51	51	51
7	125, 128, 133, 136	RL					236	236	236
8	126, 134	RL					32	32	32
9	127, 135	RL					16	16	16
10	141, 144	RL					64	64	64

Table E.38: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 1

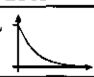
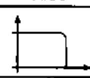
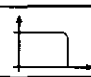
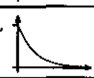
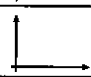
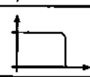
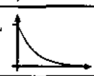
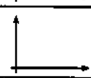
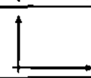
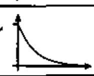
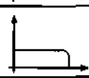
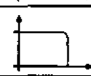
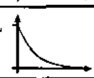
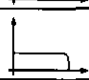
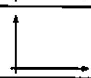
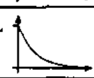
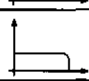
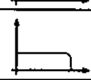
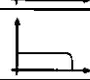
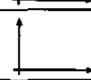
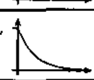
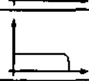
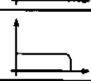
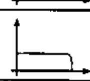
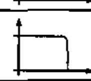
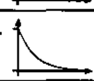
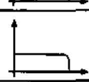
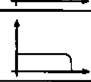
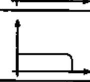
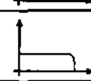
	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	nc_i	Number of Actual Possibilities na_i
11	142	RL 					16	16	16
12	143	RL 					8	8	8
13	145, 148	RL 					178	178	178
14	146	RL 					48	48	48
15	147	RL 					24	24	24
16	129, 132	RL 					160	160	160
17	130	RL 					32	32	32
18	131	RL 					26	26	26
						Effectiveness Index I_E	1.000		

Table E.39: Flow and level patterns for the main tank when there is a non-linearly decreasing level and partial flow out of the tank in the ACTIVE operating mode - Table 2

Appendix F

DORMANT Fuel Rig Results

F.1 Results for Both Lines

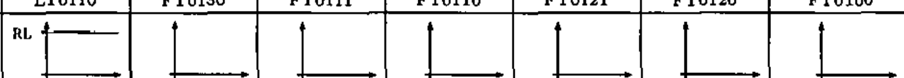
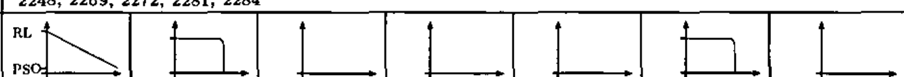
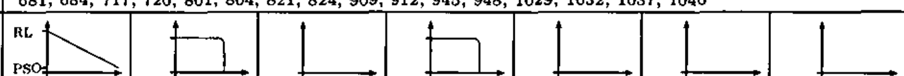
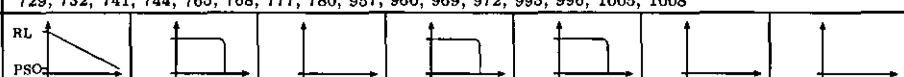
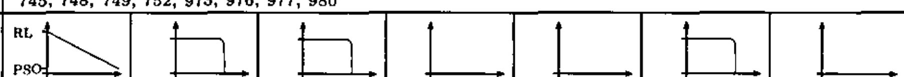
	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-								-	-	-
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284									
1								2	2	2
Scenarios	681, 684, 717, 720, 801, 804, 821, 824, 909, 912, 945, 948, 1029, 1032, 1037, 1040									
2								2	2	2
Scenarios	729, 732, 741, 744, 765, 768, 777, 780, 957, 960, 969, 972, 993, 996, 1005, 1008									
3								2	2	2
Scenarios	745, 748, 749, 752, 973, 976, 977, 980									
4								2	2	2
Scenarios	829, 832, 837, 840, 845, 848, 853, 856									
							Effectiveness Index I_E	1.000		

Table F.1: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the DORMANT operating mode

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284									
1	RL							16	16	16
Scenarios	681, 684, 717, 720, 801, 804, 821, 824, 909, 912, 945, 948, 1029, 1032, 1037, 1040									
2	RL							4	4	4
Scenarios	832, 840, 848, 856									
3	RL							2	2	2
Scenarios	831, 839, 847, 855									
4	RL							16	16	16
Scenarios	729, 732, 741, 744, 765, 768, 777, 780, 957, 960, 969, 972, 993, 996, 1005, 1008									
5	RL							4	4	4
Scenarios	746, 750, 975, 978									
6	RL							2	2	2
Scenarios	747, 751, 976, 979									
							Effectiveness Index I_E	1.000		

Table F.2: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the DORMANT operating mode

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284									
1	RL PSO							8	8	8
Scenarios	1065, 1068, 1101, 1104, 1221, 1224, 1237, 1240, 1445, 1448, 1481, 1484, 1601, 1604, 1621, 1624									
2	RL PSO							11	11	11
Scenarios	1069, 1072, 1105, 1225, 1228, 1241, 1244, 1449, 1452, 1485, 1488, 1605, 1608, 1625, 1628									
3	RL PSO							12	12	12
Scenarios	1089, 1092, 1229, 1232, 1469, 1471, 1613, 1616									

Table F.3: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the DORMANT operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
4	RL PSO							8	8	8
Scenarios	1113, 1116, 1125, 1128, 1149, 1152, 1161, 1164, 1493, 1496, 1505, 1508, 1529, 1532, 1541, 1544									
5	RL PSO							11	11	11
Scenarios	1165, 1168, 1177, 1180, 1201, 1204, 1213, 1216, 1545, 1548, 1557, 1560, 1581, 1584, 1593, 1596									
6	RL PSO							1	1	1
Scenarios	1261, 1264, 1289, 1292									
7	RL PSO							12	12	12
Scenarios	1357, 1360, 1369, 1372, 1393, 1396, 1405, 1408									
8	RL PSO							1	1	1
Scenarios	1373, 1376, 1377, 1380									
							Effectiveness Index I_E	1.000		

Table F.4: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the DORMANT operating mode - Table 2

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	RL							-	-	-
Scenarios	1, 4, 13, 16, 37, 40, 49, 52, 157, 160, 169, 172, 193, 196, 205, 208, 469, 472, 481, 484, 505, 508, 517, 520, 625, 628, 637, 640, 661, 664, 673, 676, 1609, 1612, 1621, 1624, 1645, 1648, 1657, 1660, 1765, 1768, 1777, 1780, 1801, 1804, 1813, 1816, 2077, 2080, 2089, 2092, 2113, 2116, 2125, 2128, 2233, 2236, 2245, 2248, 2269, 2272, 2281, 2284									
1	RL							2	2	2
Scenarios	1069, 1072, 1105, 1225, 1228, 1241, 1244, 1449, 1452, 1485, 1488, 1605, 1608, 1625, 1628									
2	RL							9	9	9
Scenarios	1089, 1092, 1229, 1232, 1469, 1471, 1613, 1616									
3	RL							2	2	2
Scenarios	1090, 1230, 1470, 1614									
4	RL							1	1	1
Scenarios	1091, 1231, 1471, 1615									
5	RL							2	2	2
Scenarios	1165, 1168, 1177, 1180, 1201, 1204, 1213, 1216, 1545, 1548, 1557, 1560, 1581, 1584, 1593, 1596									

Table F.5: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the DORMANT operating mode - Table 1

	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	RECYCLE L2 FT0121	STREAM FLOW L2 FT0120	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
6	RL							9	9	9
Scenarios	1357, 1360, 1369, 1372, 1393, 1396, 1405, 1408									
7	RL							2	2	2
Scenarios	1358, 1370, 1394, 1406									
8	RL							1	1	1
Scenarios	1359, 1371, 1395, 1405									
							Effectiveness Index I_E	1.000		

Table F.6: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the DORMANT operating mode - Table 2

F.2 Results for an Individual Line

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204	RL					-	-	-
1	49, 52, 61, 64, 85, 88, 97, 100	RL PSO					2	2	2
2	53, 56, 89, 92	RL PSO					2	2	2
3	65, 68, 69, 72	RL PSO					2	2	2
						Effectiveness Index I_E	1.000		

Table F.7: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the DORMANT operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204	RL					-	-	-
1	49, 52, 61, 64, 85, 88, 97, 100	RL					16	16	16
2	50, 62, 86, 98	RL					4	4	4
3	51, 63, 87, 99	RL					2	2	2
4	53, 56, 89, 92	RL					16	16	16
5	54, 90	RL					4	4	4
6	55, 91	RL					2	2	2
						Effectiveness Index I_E	1.000		

Table F.8: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the DORMANT operating mode

	Scenarios	LEVEL LT0110	MAIN FLOW FT0130	RECYCLE L1 FT0111	STREAM FLOW L1 FT0110	DRAIN FLOW FT0100	Results n_i	Results nc_i	Number of Actual Possibilities na_i
-	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204	RL					-	-	-
1	101, 104, 113, 116, 137, 140, 149, 152	RL PSO					31	31	31
2	105, 108, 141, 144	RL PSO					8	8	8
3	109, 112, 145, 148	RL PSO					11	11	11
4	129, 132	RL PSO					16	16	16
						Effectiveness Index I_E	1.000		

Table F.9: Flow and level patterns for the main tank when there is a linearly decreasing level and flow out of the tank in the DORMANT operating mode

	Scenarios	LEVEL	MAIN FLOW	RECYCLE L1	STREAM FLOW L1	DRAIN FLOW	Results		Number of Actual Possibilities
		LT0110	FT0130	FT0111	FT0110	FT0100	n_i	nc_i	na_i
-	1, 4, 13, 16 33, 36, 45, 48 153, 156, 165, 168 189, 192, 201, 204	RL					-	-	-
1	101, 104, 113, 116, 137, 140, 149, 152	RL					11	11	11
2	102, 114, 138, 150	RL					2	2	2
3	103, 115, 139, 151	RL					1	1	1
4	105, 108, 141, 144	RL					64	64	64
5	109, 112, 145, 148	RL					2	2	2
6	129, 132	RL					9	9	9
7	130	RL					2	2	2
8	131	RL					1	1	1
						Effectiveness Index I_E	1.000		

Table F.10: Flow and level patterns for the main tank when there is a non-linearly decreasing level and flow out of the tank in the DORMANT operating mode